An Investigation of the Elementary Photoproduction of Strangeness in the Threshold Region

A Dissertation
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Abstract

Investigation of kaon production on the nucleon by the electromagnetic interaction provides invaluable information on the production mechanism, the missing resonances problem and the production mechanism of a quark pair. Especially, kaon photoproduction play an important role in the threshold region, can be described by only four elementary amplitudes In principle, these amplitudes can be experimentally determined “completely” by the measurement of sixteen observables (differential cross section, three single- and twelve double-polarizations). However, the amplitudes of the $\gamma p \to K^+\Lambda$ reaction with several kinds of observables cannot even be interpreted in spite of the theoretical efforts. To overcome the current situation, the experimental data of various set such as for other isospin channels have been eagerly awaited.

The $\gamma n \to K^0\Lambda$ reaction among the six isospin channels plays an important role in investigating the production mechanism due to the following unique features. The $K\Lambda$ (isospin:$I=1/2$) production channel is simpler than the $K\Sigma$ ($I=3/2$) channel because the contributions of $\Delta^*$ ($I=3/2$) resonances are forbidden. The elementary amplitudes of the $K^0\Lambda$ reaction are constrained by those of the $K^+\Lambda$ reaction because no charge in the initial and final states are involved and the isospin symmetry are considered.

Based on the success of the previous $K^0$ measurement using a neutral kaon spectrometer (NKS), we had designed and constructed a new neutral kaon spectrometer (NKS2) at the Laboratory of Nuclear Science, Tohoku University (LNS-Tohoku). NKS2 has the larger acceptance in the forward region than that of NKS. The tagged photon beams in the photon energy region from 0.8 to 1.1 GeV and bombarded the liquid deuterium target located at the center of the spectrometer. The experiment was carried out to detect $K^0$ and $\Lambda$ in the decay channels of $K^0 \to \pi^+\pi^-$ and $\Lambda \to p\pi^-$. The $K^0$ momentum spectra were obtained for the two photon energy regions, $0.90 < E_\gamma \leq 1.00$ GeV and $1.00 < E_\gamma \leq 1.08$ GeV, with an extensive coverage for the $K^0$ production angle. The $K^0$ momentum spectra in the angular region of $0.9 < \cos \theta_{K^0}^{\text{Lab}} \leq 1.0$ and in the photon region of $0.9 < E_\gamma \leq 1.0$ GeV were compared with those of NKS. The two results show good agreement within statistical errors. The $\Lambda$ momentum spectra were also derived for the two photon energy regions for the first time. The integral cross sections of the $\gamma d \to K^0X$ reaction over the angular region of $0.5 < \cos \theta_{K^0}^{\text{Lab}} < 1.0$ in the laboratory system and the total cross sections of the $\gamma d \to \Lambda X$ reaction were also deduced for the first time.

The integral cross section of the $K^0$ production on the deuteron was compared with the total cross section of the $\gamma p \to K^+\Lambda$ reaction. They agree each other in the energy region of $E_\gamma < 1.0$ GeV reasonably well. It suggests that the energy dependence of the $\gamma n \to K^0\Lambda$ reaction is almost the same as that of the $\gamma p \to K^+\Lambda$ in the threshold region. On the other hand, the angular distributions of the $K^0\Lambda$ and $K^+\Lambda$ reactions in the center of mass system (c.m.) show different shapes. The $K^0\Lambda$ reaction, which is indicated by the global fit of the $\gamma d \to K^0X$ momentum spectra, shows the backward angular distribution in the c.m. system while the $K^+\Lambda$ shows the slight forward.

The present results were compared with the theoretical calculation based on the elementary amplitudes of isobar models, i.e. Kaon-MAID and SLA, folding a realistic deuteron wave function. Our results for the inclusive $K^0$ and $\Lambda$ measurements favor the calculations predicted by the SLA model after adjusting the free parameter. Moreover, the calculations with the RPR model were compared with the results in the energy region of $E_\gamma=0.9$–1.0 GeV and in the angular region of $0.9 < \cos \theta_{K^0}^{\text{Lab}} \leq 1.0$. The present results were at least 2 times larger than
the calculations.
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Chapter 1

Introduction

1.1 Investigation of kaon production by the electromagnetic interaction

Kaon production by the electromagnetic interaction plays an important role in not only the production mechanism but also the search for missing resonances.

The kaon photoproduction in the threshold region has being labeled by the isospin as follows,

\[
\begin{align*}
\gamma + p &\rightarrow K^+ + \Lambda & 911.1 \text{ MeV} \\
\gamma + p &\rightarrow K^+ + \Sigma^0 & 1046.2 \text{ MeV} \\
\gamma + p &\rightarrow K^0 + \Sigma^+ & 1047.5 \text{ MeV} \\
\gamma + n &\rightarrow K^0 + \Lambda & 915.3 \text{ MeV} \\
\gamma + n &\rightarrow K^0 + \Sigma^0 & 1050.6 \text{ MeV} \\
\gamma + n &\rightarrow K^+ + \Sigma^- & 1052.1 \text{ MeV}.
\end{align*}
\]

Spins of a photon ($\gamma$), a nucleon ($p, n$), a kaon ($K^+, K^0$) and a hyperon ($\Lambda, \Sigma^{0,\pm}$) are 1, 1/2, 0 and 1/2, respectively. Because a real photon does not have the longitudinal component, the $\Delta S_z=0$ state is forbidden. Therefore, the elementary amplitudes of kaon photoproductions are fully described only by the eight spin states. In the other word, these productions are represented only by the four amplitudes, which consist of the real and imaginary parts by each amplitude. On the other hand, not only the differential cross section but also three single- and twelve double-polarization observables can be experimentally determined (see Table 1.1). These obervables can be measured by taking the advantage of the self-analyzing nature of the $\Lambda$ or $\Sigma$ particles. In the case of pion photoproduction, which is the same pseudoscaler meson photoproduction as the kaon, the recoil polarization observables and the measurements of the beam-recoil and target-recoil asymmetries are so difficult due to without this nature. Thus, kaon photoproduction is unique in the sense that the elementary amplitudes can be “completely” determined by the measurement of these observables and the strangeness production mechanism can be well investigate.

In addition, there is a long standing problem in the hadron physics which is called “missing resonances” problem. The quark model calculations have predicted many baryon resonance states. Even though some resonances have been found in pion-scattering, many others have
CHAPTER 1. INTRODUCTION

not. S. Capstick and W. Roberts have suggested some of the missing resonances may decay to other channels such as $\pi\pi N$, $\eta N$ and $KY$ due to the weak coupling to $\pi N$ [1, 2]. The significant advantage of kaon photo- and electroproductions in the search for the missing resonances is the isospin selectivity for the difference between $\Lambda(I=0)$ and $\Sigma(I=1)$. The $K\Lambda$ production channel has isospin $I=1/2$ and so only $N^*(I=1/2)$ can participate in the $s$-channel. While, the $K\Sigma$ channel with isospin $I=3/2$ needs the contributions by both $N^*(I=1/2)$ and $\Delta^*(I=3/2)$ resonances. Moreover, a two-body final state is simpler for theoretical approaches and easier for experiments than the more complex multi-pion final states.

As the recent topics, the production mechanisms of the strange quark-antiquark pair ($s\bar{s}$) has been reported by the observation of the transferred polarization in the $\vec{e}p \rightarrow e^{'K^+}\bar{\Lambda}$ reaction [3]. Since many hadron decays are described successfully in terms of the $^3P_0$ model, the $s\bar{s}$ pair is predominantly produced with its spins anti-aligned as this experimental results. It suggested that the mechanisms of the baryon decays and the $s\bar{s}$ pair production is not understood.

Figure 1.1: Total cross sections for six isospin channels of kaon photoproduction. The green open circles [32, 33] and the black closed boxes [34, 35] represent the experimental data of SAPHIR. The red closed circles and the blue closed triangles was obtained at CLAS [42] and CB-TAPS [39]. The solid lines represent the theoretical calculation of the isobar model by Kaon-MAID [45, 63].

1.2 Historical background

1.2.1 Previous experimental investigations

1.2.1.1 Before 1990s

Experimental investigations of kaon productions by the electromagnetic interaction have been started using the proton target since the late 1950s [4, 5]. Last three decades after that, the
1.2. HISTORICAL BACKGROUND

Table 1.1: Overview of polarization observables for photoproductions

<table>
<thead>
<tr>
<th>observable</th>
<th>symbol</th>
<th>required polarizations</th>
</tr>
</thead>
<tbody>
<tr>
<td>differential cross section</td>
<td>( \frac{d\sigma}{d\Omega} )</td>
<td>– – –</td>
</tr>
<tr>
<td>single polarization</td>
<td>( \Sigma )</td>
<td>linear – –</td>
</tr>
<tr>
<td></td>
<td>( T )</td>
<td>linear along ( y' ) –</td>
</tr>
<tr>
<td></td>
<td>( P )</td>
<td>linear – along ( y' )</td>
</tr>
<tr>
<td>beam-target polarization</td>
<td>( G )</td>
<td>linear along ( z' ) –</td>
</tr>
<tr>
<td></td>
<td>( H )</td>
<td>linear along ( x' ) –</td>
</tr>
<tr>
<td></td>
<td>( E )</td>
<td>circular along ( z' ) –</td>
</tr>
<tr>
<td></td>
<td>( F )</td>
<td>circular along ( x' ) –</td>
</tr>
<tr>
<td>beam-recoil polarization</td>
<td>( O_{x'} )</td>
<td>linear – along ( x' )</td>
</tr>
<tr>
<td></td>
<td>( O_{z'} )</td>
<td>linear – along ( z' )</td>
</tr>
<tr>
<td></td>
<td>( C_{x'} )</td>
<td>circular – along ( x' )</td>
</tr>
<tr>
<td></td>
<td>( C_{z'} )</td>
<td>circular – along ( z' )</td>
</tr>
<tr>
<td>target-recoil polarization</td>
<td>( T_{x'} )</td>
<td>– along ( x' ) along ( x' )</td>
</tr>
<tr>
<td></td>
<td>( T_{z'} )</td>
<td>– along ( x' ) along ( z' )</td>
</tr>
<tr>
<td></td>
<td>( L_{x'} )</td>
<td>– along ( z' ) along ( x' )</td>
</tr>
<tr>
<td></td>
<td>( L_{z'} )</td>
<td>– along ( z' ) along ( z' )</td>
</tr>
</tbody>
</table>

The coordinate system can be see Ref. [71].

differential cross sections for the \( \gamma p \rightarrow K^+ \Lambda (\Sigma^0) \) reactions near the threshold were measured at CalTech [6–9], Cornell [10,11], Bonn [12,13], Tokyo [14] and DESY [15]. In the higher photon energy region, the differential cross sections were provided by SLAC (\( 5 < E_\gamma < 16 \) GeV) [16,17], DESY (\( E_\gamma \approx 6.0 \) GeV) [18], ABBHHM (\( 0.3 < E_\gamma < 5.8 \) GeV) [19] and CEA (\( 3.4 < E_\gamma < 4.0 \) GeV) [20].

The single polarization measurements for the \( \gamma p \rightarrow K^+ \Lambda (\Sigma^0) \) reactions were also published. The recoil polarization (\( P \)) was measured at the threshold region [9,14,21,22] and at the high energy region [23,24]. The beam asymmetry (\( \Sigma \)) using a linearly polarized photon beam was also obtained at the high energy region by the SLAC group [24]. Although the statistics was poor, the target asymmetry (\( T \)) was measured using the butanol polarized-proton target near the threshold by the Bonn group [25] and at the high energy by the SLAC group [9].

As other channels, the total cross section in the \( \gamma p \rightarrow K^0 \Sigma^+ \) reaction existed was obtained, though the statistics was poor [19]. The inclusive \( K^+ \) measurements on the deuteron, which includes the \( K^+ \Sigma^- \) and \( K^+ \Sigma^0 \) reactions, were published by the SLAC group [24,26].

Furthermore, a few \( p(e,e'K^+)\Lambda/\Sigma^0 \) data were published in 1970s by the CEA [27], Cornell [28,29], and DESY groups [30].

1.2.1.2 Recent experiment

The theoretical investigations of kaon productions had not progressed due to the lack of precise experimental data until 1990s. Since 1990s, new experiments have been carried out at various high-energy, high-duty cycle accelerator facilities such as CEBAF (CLAS), ELSA (SAPHIR, CB-TAPS), ESRF (GRAAL) and SPring-8 (LEPS).
Firstly, the Bonn group provided the high-quality data using SAPHIR (Spectrometer Arrangement for PHoton Induced Reactions) [31]. The total and differential cross sections and the hyperon polarization ($P$) in the $\gamma p \rightarrow K^+\Lambda$ and $\gamma p \rightarrow K^+\Sigma^0$ reactions were measured for the full angular range in the photon energy range from the reaction threshold up to 2.0 GeV [32]. The total cross section of the $K^+\Lambda$ reaction indicated an apparent bump structure around $W=1900$ MeV. This structure was interpreted as the missing resonance through the model calculations by T. Mart and C. Bennhold et al. [45]. Additionally, the total and differential cross sections of the $K^+\Sigma$ reaction were also obtained [33]. The polarization observables of $\Sigma^+$ hyperon were determined for the first time. Later, the results of the new dataset were reported with much richer statistics and an extended photon energy range up to 2.6 GeV [34,35]. Recently, the total and differential cross sections and recoil polarization ($P$) of the $\gamma p \rightarrow K^0\Sigma^+$ channel were provided with a new spectrometer, Crystal Barrel [36] and TAPS [37] photon spectrometers [38]. The experiments with linearly and circularly polarized photon beams and the longitudinally polarized target have been performed in order to investigate the reaction amplitudes of kaon photoproductions [39].

At Thomas Jefferson Laboratory (JLab), kaon photoproductions have been investigated systematically using CEBAF Large Acceptance Spectrometer (CLAS) [40] and high-quality photon and electron beams, which can provide linearly and circular polarized photon beams with a coherent bremsstrahlung system. The total and differential cross sections and the hyperon polarization ($P$) in the $\gamma p \rightarrow K^+\Lambda$ and $\gamma p \rightarrow K^+\Sigma^0$ reactions with high statistics were provided in the photon energy range from the reaction threshold up to 2.95 GeV [41–44]. However, the cross section of the $K^+\Lambda$ reaction around $W=1900$ GeV from CLAS was larger than that by the SAPHIR group by a factor of about 30% (see Fig. 1.2(a)). This difference becomes much more pronounced in the forward region which is significant for establishing the role of the $t$-channel in the production mechanism. The results from CLAS predicted that the bump structure around $W=1900$ MeV, which was interpreted as the evidence for a missing resonance for the SAPHIR data, varied in mass and width with kaon angle. It suggested an interference phenomenon between several resonant states in this mass range [46]. The experiment to measure the spin transfer from circularly polarized real photons to recoiling hyperons ($C_\Sigma, C_\Lambda$) was carried out for the $\gamma p \rightarrow K^+\Lambda$ and $\gamma p \rightarrow K^+\Sigma^0$ reactions for the first time [47]. The differential cross sections of the $\gamma n \rightarrow K^+\Sigma^-$ reaction in the incident photon energy between 1.1 and 3.6 GeV on the deuteron were measured covering a broad angular range [48]. Moreover, the electroproductions of the $ep \rightarrow e'K^+\Lambda$ and $ep \rightarrow e'K^+\Sigma^0$ reactions were provided using a polarized electron beam [3,49–52] to investigate not only longitudinal components but also transverse and interference structure functions. Additionally, the experiments of the $ep \rightarrow e'K^+\Lambda$ and $ep \rightarrow e'K^+\Sigma^0$ reactions at JLab using two arms spectrometer, HMS and SOS [53, 54], and HRS [55] were carried out by other groups.

By the LEPS group of RCNP, Osaka, the differential cross sections and the beam asymmetries ($\Sigma$) for the $\gamma p \rightarrow K^+\Lambda$ and $\gamma p \rightarrow K^+\Sigma^0$ reactions were measured using a linearly polarized photon beam of $E_\gamma=1.5–2.4$ GeV with a magnetic spectrometer, which is called LEPS [56] They discussed the contributions of $t$- and $u$-channel diagrams which are dominant at forward region [57] and backward [58] in the center of mass system, respectively. Moreover, for the first time, the differential cross sections and the beam asymmetries for the $\gamma n \rightarrow K^+\Sigma^-$ reaction on the deuteron were measured and compared with the $\gamma p \rightarrow K^+\Sigma^0$ reaction [59].

GRAAL collaboration focused the importance of polarization observables. Firstly, they measured the beam asymmetries ($\Sigma$) and the hyperon recoil polarizations ($P$) for the $\gamma p \rightarrow K^+\Lambda$ and $\gamma p \rightarrow K^+\Sigma^0$ reactions from the threshold to 1.5 GeV [60]. Additionally, the measure-
ments of the beam-recoil observables $O_x$, $O_z$ via the $\gamma p \to K^+ \Lambda$ reaction and the target asymmetries ($T$), which could also be extracted despite the use of an unpolarized target, were provided \[61\]. To check the compatibility of the various spin observables, the consistency with the results published by CLAS was confirmed.

The accelerators and the measured quantities of the high-quality data since 1990s are summarized in Table 1.2. Additionally, the total cross sections for six isospin channels of kaon photoproductions are shown in Fig. 1.2.

Table 1.2: Recent experimental investigations of the kaon photoproductions. Accelerators, facilities, elementary processes, photon energy regions and observables are summarized

<table>
<thead>
<tr>
<th>accelerator/detector</th>
<th>$E_\gamma$ [GeV]</th>
<th>process</th>
<th>measured quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELISA/SAPHIR</td>
<td>- 2.6</td>
<td>$\gamma p \to K^+\Lambda/\Sigma^+$</td>
<td>$\sigma_{\text{tot}}$, $\frac{d\sigma}{d\Omega}$, $P_{\Lambda/\Sigma^0/\Sigma^+}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\gamma p \to K^0\Sigma^+$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\gamma n \to K^+\Sigma^-$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\gamma p \to K^+\Lambda/\Sigma^0$</td>
<td>$\sigma_{\text{tot}}$, $\frac{d\sigma}{d\Omega}$, $P_{\Lambda/\Sigma^0}$, $C_x$, $C_z$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\gamma p \to K^0\Sigma^+$</td>
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<tr>
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<td>$\gamma p \to K^+\Sigma^-$</td>
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<td>$\gamma n \to K^+\Sigma^-$</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\gamma p \to K^0\Sigma^0$</td>
<td>$\sigma_{\text{tot}}$, $\frac{d\sigma}{d\Omega}$, $P_{\Sigma^0}$</td>
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<tr>
<td></td>
<td></td>
<td>$\gamma p \to K^+\Sigma^0$</td>
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<td>$\gamma p \to K^0\Sigma^0$</td>
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<td>$\gamma p \to K^+\Sigma^0$</td>
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<tr>
<td></td>
<td></td>
<td>$\gamma p \to K^0\Sigma^+$</td>
<td></td>
</tr>
</tbody>
</table>

† extracted quantity despite the use of an unpolarized target

### 1.2.2 Previous theoretical investigations

#### 1.2.2.1 Hadrodynamic models

An isobar model has the amplitudes derived from an effective hadronic Lagrangian using the Feynman diagram technique in the tree level approximation. Feynman diagrams used by this model are shown in Fig. 1.3. In this model, baryons and mesons, which are not only ground states (Born terms) but also resonance states (resonance terms), are exchanged as intermediate states.

The well-known fact in kaon photoproductions, compared to the $\pi$ and $\eta$ productions, is that the reaction mechanism is not dominated by a small number of resonances. Therefore, the contributions by the large number of the resonances lead to complexity of the theoretical works. In fact, after the pioneer and significant work preformed by H. Thom \[21\], the theoretical analysis made little progress for almost two decades. The construction of new electron accelerator facilities in 1990s helped the propose of the numerous theoretical attempts. The constraints from the crossing symmetry \[64,65\] and the duality hypothesis \[64\] were introduced so as to reduce the parameters. The high spin states of nucleon \[65,66\] and hyperon resonances \[67\] were adopted. Moreover, the hadronic form factors and the contact terms were included \[68–70\]. Then, many kind of the isobar model were proposed \[64,65,71–75\].

As described above, the total cross section of the $\gamma p \to K^+\Lambda$ reaction by the SAPHIR group has the structure at around 1900 MeV. Firstly, T. Mart and C. Bennhold et al. pointed
out that this structure of the $K^+\Lambda$ production could be explained by the $D_{13}(1960)$ “missing” resonance [45]. On the other hand, B. Saghai et al. refitted the same cross section data and showed the reproduction in the condition of no $D_{13}(1895)$ resonance by tuning the background processes [65]. Furthermore, S. Janssen et al. fitted calculations to not only the differential cross section but also photon beam asymmetry [62] and electroproduction data [54]. They indicated the possibility for one or more of $S_{11}$, $P_{11}$, $P_{13}$, or $D_{13}(1895)$ resonances [76]. Here, the $P_{11}(1895)$ solution becomes the best fit. More comprehensive measurements, such as various polarization observables, would be required to make further progress.

Since the cross section for the pion photoproductions are two orders of magnitude larger than that of kaon photoproductions, the process of the $\pi N \rightarrow KY$ rescattering will be significant in the higher-order mechanisms. W. T. Chiang et al. [77] showed that the contribution of the intermediate $\pi N$ channel to the $\gamma p \rightarrow K^+\Lambda$ cross sections is of the order of 20%. However, the coupled channel approach suffers from the inclusion of a large number of resonances. Several groups are presently making an effort to extract the resonance parameters in the coupled channels analysis [78–81].

### 1.2.2.2 Regge model and Regge-plus-resonance model

The Regge model is based on the idea of exchange of families of the particles with particular quantum numbers in the $t$-channel channel [82, 83]. The Regge model is aimed mainly for the high energy region ($E_\gamma > 4$ GeV) at the forward angle. Feynman diagram used by this model is shown in Fig. 1.4. In this model of the $\gamma p \rightarrow K^+\Lambda(\Sigma^0)$ process, the $K(494)$ and $K^*(892)$ trajectories are exchanged. Moreover, the electric part of the $s$-channel Bron term is added to
1.2. HISTORICAL BACKGROUND

Figure 1.3: Feynman diagrams contributing to kaon photoproductions in isobar models. The upper rows(a)(b)(c) show the Born terms, and the lower rows(d)(e)(f) correspond to the resonance terms. The left figures(a)(d) correspond to s-channel nucleon or nucleon resonances exchanges. The middle one(b)(e) typify t-channel meson exchanges and the right one(c)(f) represent the u-channel hyperons or hyperon resonances exchanges.

The coupling constants are obtained by fitting as parameters against the high-energy observables [16]. The number of free parameters is smaller than hadrodynamic models.

However, in the resonance region, the description of the Regge-trajectory exchange can no longer be expected to account for all aspects of the reaction dynamics as the asymptotic form of $s \rightarrow \infty$ and $|t| \rightarrow 0$. At low energy region, the cross sections have complex structures, such as peaks at certain energies. Because the resonant contributions in the s-channel are dominant in this region. Therefore, the contributions of s-channel resonance are added to the amplitude of the Regge model in order to extend toward the resonance region. This hybrid approach is called the “Regge-plus-resonance” (RPR) model. This model has a great advantage much less free parameters for the background amplitudes. This model have been developed not only for the $K\Lambda$ process [84,85] but also for the $K\Sigma$ [86,87].

In the $K\Lambda$ process, this model includes the nucleon resonance $S_{11}(1650), P_{11}(1710), P_{13}(1720), P_{13}(1900)$ and $D_{13}(1900)$. In the first time, this model was developed with the other option with the $P_{11}(1900)$ state instead of the $D_{13}(1900)$ and was compared with the results of the electroproduction by CLAS. the $D_{13}(1900)$ assumption could be reconciled with the data, whereas the $P_{11}(1900)$ option could be clearly be rejected [88]. Moreover, the resonances identifying the $S_{11}(1650), P_{11}(1710), P_{13}(1720), P_{13}(1900), D_{33}(1700), S_{31}(1900), P_{31}(1910)$ and $P_{33}(1920)$ are added as essential contributions for the $K\Sigma$ processes.

$$M = M_{\text{Regge}}^{K^+(494)} + M_{\text{Regge}}^{K^+(892)} + M_{\text{Regge}}^{p,\text{elec}} \times M_{\text{Regge}}^{K^+(494)} \times (t - m_{K^+}^2) \quad (1.1)$$

The number of free parameters is smaller than hadrodynamic models.

In the $K\Lambda$ process, this model includes the nucleon resonance $S_{11}(1650), P_{11}(1710), P_{13}(1720), P_{13}(1900)$ and $D_{13}(1900)$. In the first time, this model was developed with the other option with the $P_{11}(1900)$ state instead of the $D_{13}(1900)$ and was compared with the results of the electroproduction by CLAS. the $D_{13}(1900)$ assumption could be reconciled with the data, whereas the $P_{11}(1900)$ option could be clearly be rejected [88]. Moreover, the resonances identifying the $S_{11}(1650), P_{11}(1710), P_{13}(1720), P_{13}(1900), D_{33}(1700), S_{31}(1900), P_{31}(1910)$ and $P_{33}(1920)$ are added as essential contributions for the $K\Sigma$ processes.
Figure 1.4: Feynman diagrams contributing to the $\gamma p \rightarrow K^0\Lambda(\Sigma^0)$ process for $E_\gamma > 4$ GeV at the forward region (Regge model). In this model, the families of $K(494)(a)$ and $K^*(892)(b)$ are exchanged. Moreover, the electric part of the $s$-channel Born term$(c)$ is added to restore gauge invariance.

1.3 Investigation of the $\gamma n \rightarrow K^0\Lambda$ process

1.3.1 Feature of the $\gamma n \rightarrow K^0\Lambda$ process near the threshold

As described in Sec.1.1, the elementary amplitudes of kaon photoproductions can be determined “completely” by the measurement of the differential cross section and polarization observables. The results with high statistics for the $\gamma p \rightarrow K^+\Lambda$ and $\gamma p \rightarrow K^+\Sigma^0$ reactions have been provided by several groups with new accelerator facilities since 1990s. Especially, the experiment of the $\gamma p \rightarrow K^+\Lambda$ reaction have been carried out through several kinds of observables ($d\sigma/d\Omega$, $P$, $\Sigma$, $T$, $C_x$, $C_z$, $O_x$ and $O_z$). However, the amplitudes of the $\gamma p \rightarrow K^+\Lambda$ reaction cannot even be interpreted in spite of the theoretical effort. To overcome the current situation, the experimental data of various set such as for other isospin channels have been eagerly awaited.

The $\gamma n \rightarrow K^0\Lambda$ reaction among the six isospin channels plays an important role in investigating the production mechanism due to the following unique features.

no contributions of $\Delta^*$ states in the $s$-channel

The $K\Lambda$ channels, $K^+\Lambda$ and $K^0\Lambda$, can only involve intermediate isospin $1/2 (N, N^*)$ states whereas the $K\Sigma$ channels can involve the excitation of both isospin $1/2 (N, N^*)$ and $3/2 (\Delta^*)$ states. It means that the $K\Lambda$ channel is simpler than the $K\Sigma$ channel because the contributions of $\Delta^*$ resonances are forbidden.

no involved charge in the initial and final states

Since $K^0$ in the final state is neutral, the Born term in the $t$-channel does not contribute and only kaon excitation states such as $K^*(892)$ and $K_1(1270)$ can contribute. The old isobar model [73] suggests the backward peak due to the absent $t$-channel contribution in the Born terms [89]. In the Regge and RPR framework, the $K(494)$ Regge trajectory in the $t$-channel exchange does no longer contribute and the $K^*(892)$ trajectory contributes efficiently. Furthermore, the electromagnetic couplings via the charged particles does not contribute except for through only anomalous magnetic moments because of no charge in initial state.
1.3. INVESTIGATION OF THE $\gamma N \rightarrow K^0\Lambda$ PROCESS

isospin symmetry

Since the $\Lambda$ is an isosinglet particle, the hadronic coupling constants in the hadronic vertices have the relations as follows,

$$g_{K^+\Lambda p} = g_{K^0\Lambda n}\quad (1.2)$$

On the other hand, the $\Sigma$ is isotriplet particles having isospin 1. Therefore, the hadronic coupling constant by the Clebch-Gordan coefficients coupling from isospin 1 plus isospin 1/2 to isospin 1/2 are as follows,

$$g_{K^+\Sigma^0 p} = -g_{K^0\Sigma^0 n}\quad (1.3)$$

In the same way, the hadronic coupling constants of the nucleon resonances, kaon resonances and the hyperon resonances in the hadronic vertices are determined (see Sec. 5.2.1 in detail).

Therefore, the $\gamma n \rightarrow K^0\Lambda$ channel can provide a more stringent constrain to elementary models which have been built on the $K^+$ productions on the proton. Thus, this channel can serve as a means for testing the available elementary models. Since off neutron cannot be used as the target, the experiment on the deuteron target is performed and the elementary cross section on the neutron can be reliably extracted from the deuteron cross section [89].

1.3.2 NKS experiment

We had constructed a Neutral Kaon Spectrometer (NKS) for the investigation of the $\gamma n \rightarrow K^0\Lambda$ channel at the Laboratory of Nuclear Science, Tohoku University (LNS-Tohoku) in 2000. NKS was based on the TAGX spectrometer [91] which was built at Electron-Synchrotron, Institute of Nuclear Study, University of Tokyo (INS-ES). The TAGX magnet and some of the detector system were moved to LNS-Tohoku after the shutdown of INS-ES. It consists of a dipole magnet ($\phi$:107 cm, gap:0.68 cm, B:0.5 Tesla), a pair of cylindrical drift chambers (CDC) and a pair of straw drift chambers (SDC) for tracking and momentum analysis and plastic scintillator hodoscopes (IH and OH) for the measurement of the time-of-flight (TOF). This spectrometer is illustrated in Fig. 1.5. The tagged photons were generated via bremsstrahlung in the energy range of 0.8-1.1 GeV. The charged particles from the $K^0 \rightarrow \pi^+\pi^-$ decay were measured by NKS.

In the first stage, the results on the carbon ($^{12}$C) provided the first information on the $\gamma n \rightarrow K^0\Lambda$ reaction near the threshold [92]. The integrated cross section of the quasi-free $\gamma n \rightarrow K^0\Lambda$ reaction were presented as the excitation function of the incident photon energy. The experimental results show the cross section of the $^{12}$C($\gamma, K^0$) is almost the same as that of the $^{12}$C($\gamma, K^+$) [93] (see Fig. 1.6). Quasi-free spectra of this reaction were calculated using a spectator model that assumes the elementary amplitudes of the $\gamma n \rightarrow K^0\Lambda$ process given by recent isobar models, and were compared with the experimental results. These results suggested that the $\gamma n \rightarrow K^0\Lambda$ reaction has the backward angular distribution in the center of mass frame (c.m.). However the analysis had a limit as the interpretation of the elementary process because the complex many-body nature of the process on the carbon have an uncertainty.

As the second step, the measurement of $K^0$ photoproduction on the deuteron was performed using NKS [94]. Figure 1.7 shows the $\pi^+\pi^-$ invariant mass spectra. The widths of $K^0$ peaks ($\sigma$) were $16.2\pm0.8$ MeV/c$^2$ in the photon energy region (a) from 0.9 to 1.0 GeV and $13.0\pm1.4$ MeV/c$^2$ in the region (b) from 1.0 to 1.1 GeV. The $K^0$ momentum spectra in the laboratory frame were obtained and compared with the theoretical calculations in order...
CHAPTER 1. INTRODUCTION

Figure 1.5: Schematic view of NKS. It consists of a dipole magnet, a pair of cylindrical drift chambers (CDC) and a pair of straw drift chambers (SDC) and plastic scintillation hodoscopes (IH and OH). It was clear that the acceptance in the forward region was extremely small to suppress the photon conversion events.

Figure 1.6: Photon energy dependence of the integrated cross sections for kaon photoproductions on the carbon. The closed circles (black) and the open triangles (red) show the results for the $K^0$ ($0.8 < \cos \theta_{\text{Lab}} < 1.0$ [92]) and the $K^+$ productions ($10^\circ \theta_{\text{Lab}} < 40^\circ$ [93]) in the laboratory frame, respectively.

to examine the angular distributions of the elementary cross section in the c.m. system (see Fig. 1.8). In the calculations, a simple spectator model in the plane wave impulse approxima-
tion was assumed and the momentum distribution of the nucleon in a deuteron was used by the relativistic Bonn deuteron wave function. The elementary amplitudes were assumed to be two recent isobar models and a simple phenomenological prescription. This comparison suggested that an enhancement of the elementary cross section in the backward hemisphere is crucial to explain the $K^0$ momentum shape.

![Figure 1.7](image1)

**Figure 1.7:** $\pi^+\pi^-$ invariant mass spectra of NKS on the deuteron in the photon energy regions (a) from 0.9 to 1.0 GeV and (b) from 1.0 to 1.1 GeV. The widths of $K^0$ peaks ($\sigma$) were (a) $16.2\pm0.8\text{ MeV}/c^2$ and (b) $13.0\pm1.4\text{ MeV}/c^2$.

![Figure 1.8](image2)

**Figure 1.8:** Momentum spectra indicated by NKS on the deuteron. in the photon energy regions (a) from 0.9 to 1.0 GeV and (b) from 1.0 to 1.1 GeV. The shape of the momentum spectra comes from the angular distribution in the c.m. system and the excitation function.

The NKS experiment was successfully carried out as the pioneer of $K^0$ photoproduction. However, the $K^0$ acceptance in the high momentum region ($p_{K^0}^{\text{lab}}>0.5\text{ GeV}/c$) was too small. Therefore, the spectra in this region had large uncertainties. These uncertainties imposed some limitations on the comparison with the theoretical calculation, since the angular distribution in the c.m. system might be discussed from the shape of the momentum spectra in the laboratory system. The limitation of the acceptance was caused by the detector configuration. NKS did not cover geometrically in the forward angle (see Fig. 1.5).

In order to overcome some limitations and further pursue the $K^0$ photoproduction, we have started the NKS2 project.
1.4 Purpose of the present experiment

The experiments for the $\gamma p \rightarrow K^+ \Lambda$ and $\gamma p \rightarrow K^+ \Sigma^0$ reactions for several kinds of observables have been performed at CEBAF, ELSA, ESRF and SPring-8. However, there had been no reliable data of other isospin channels and the theoretical investigation suffered seriously from the lack of the data. The $\gamma n \rightarrow K^0 \Lambda$ reaction among the six isospin channels plays an important role in investigating the production mechanism because no charge in the initial and final states are involved. The motivation of the present study pursues the inclusive interpretation of kaon photoproductions from the $\gamma n \rightarrow K^0 \Lambda$ channel.

As describe above, we had designed and constructed a new neutral kaon spectrometer (NKS2), which has the larger acceptance in the forward region than the that of the previous one (NKS). Tagged photons in the 1 GeV region were delivered to the liquid deuterium target at LNS-Tohoku. The experiment was carried out to measure $K^0$ and $\Lambda$ in the charged decay channels in 2006 and 2007. In this experiment, we will provide the following results,

- $K^0$ momentum spectra of the same region as that of NKS with the alleviate uncertainties of the high momentum region,
- $K^0$ momentum spectra with an extensive $K^0$ production angle,
- $K^0$ integral cross section,
- $\Lambda$ momentum spectra,
- $\Lambda$ integral cross section.

The information of the $\gamma n \rightarrow K^0 \Lambda$ process with a new dimension will be extracted from these inclusive $K^0$ and $\Lambda$ measurements.
Chapter 2

Experimental apparatus

In this chapter the experimental method for the measurement of $K^0$ and $\Lambda$ is explained. The experimental apparatus is described.

Firstly, how to measure $K^0$ and $\Lambda$ is discussed in Sec. 2.1.

We had designed and constructed a new magnetic spectrometer, which is called NKS2, for the measurement of the charged decay modes of $K^0$ and $\Lambda$ at the Laboratory of Nuclear Science, Tohoku University (LNS-Tohoku) \textsuperscript{†}. The detectors system of NKS2 is described in Sec. 2.4. This experiment was carried out using a 0.8-1.1 GeV tagged photon beam via bremsstrahlung at the second experimental hall of LNS-Tohoku. The generating and tagging systems of photons are described in Sec. 2.2. The beam line setup is explained in Sec. 2.3. The cryogenic system for the liquid deuterium target was used in order to investigate the elementary process of the $\gamma n \to K^0 \Lambda$ reaction. In Sec. 2.5, this system is introduced. The electronics for each detector and the trigger conditions are explained in Sec. 2.6. Moreover, the data acquisition system is described in this section.

Finally, this chapter is concluded with the data summary in Sec. 2.7.

2.1 Experimental method

In this experiment, the $\gamma n \to K^0 \Lambda$ process near the threshold energy on the deuteron was investigated by detecting the charged decay modes of $K^0$ and $\Lambda$.

The state of generated $K^0$ is described as the linear combination of $K^0_S$ and $K^0_L$, which are the different $CP$ eigenstates. Therefore, the probability of $K^0_S$ is 50% in total of generated $K^0$. In the assumption of $CP$ conservation, $K^0_S$ and $K^0_L$ have the hadronic decay modes into two and three pions, respectively. The $K^0_L \to \pi^+ \pi^−$ decay is suppressed by three orders of magnitude due to $CP$ violation. Table 2.1 shows the properties of $K^0_S$ and $K^0_L$ \cite{90}. In this experiment, $\pi^+$ and $\pi^−$ via the $K^0_S \to \pi^+ \pi^−$ decay mode were detected, then the $K^0$ event was identified by the reconstruction of the invariant mass.

A hyperon, which is a baryon containing one or more strange quarks, is generated with anti-strange quark by the kaon photoproductions introduced in Sec. 1.1, since the strangeness should be conserved in the electromagnetic interaction. In the energy region of this experiment, $\Lambda$ and $\Sigma$ with one strange quark are generated. Only $\Lambda$ with the decay mode into charged particles ($p$ and $\pi^−$) can be identified in the present analysis. It is important that $\Sigma^0$ decays into $\Lambda \gamma$ at the branching ratio of 100\%, because this $\Lambda$ from $\Sigma^0$ decay cannot distinguished from $\Lambda$.

\textsuperscript{†}Present Name: Research Center of Electron Photon Science, Tohoku University (ELPH)
CHAPTER 2. EXPERIMENTAL APPARATUS

photoproduction by the inclusive measurement. Table 2.2 shows the properties of Λ, Σ⁺ and Σ⁰ [90].

Table 2.1: Properties of $K_S^0$ and $K_L^0$ [90]

<table>
<thead>
<tr>
<th></th>
<th>$K_S^0$</th>
<th>$K_L^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>497.614 ± 0.024 MeV</td>
<td></td>
</tr>
<tr>
<td>Life Time</td>
<td>$cτ$=2.6842 cm</td>
<td>$cτ$=1534 cm</td>
</tr>
<tr>
<td>Decay Mode</td>
<td>$π^+π^-(69.20 \pm 0.05%)$</td>
<td>$3π^0(19.52 \pm 0.12%)$</td>
</tr>
<tr>
<td></td>
<td>$π^0π^0(30.69 \pm 0.05%)$</td>
<td>$π^+π^−π^0(12.54 \pm 0.05%)$</td>
</tr>
<tr>
<td></td>
<td>$π^±e^±ν_e(40.55 \pm 0.12%)$</td>
<td>$π^±μ^±ν_μ(27.04 \pm 0.07%)$</td>
</tr>
</tbody>
</table>

Table 2.2: Properties of Λ, Σ⁺ and Σ⁰ [90]

<table>
<thead>
<tr>
<th></th>
<th>Λ</th>
<th>Σ⁺</th>
<th>Σ⁰</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>1115.683 ± 0.006 MeV</td>
<td>1189.37 ± 0.07 MeV</td>
<td>1192.642 ± 0.024 MeV</td>
</tr>
<tr>
<td>Life Time</td>
<td>$cτ$=7.89 cm</td>
<td>$cτ$=2.404 cm</td>
<td>$τ=(7.4 \pm 0.7)\times10^{-20}$ s</td>
</tr>
<tr>
<td>Decay Mode</td>
<td>$pπ^-(63.9 \pm 0.5%)$</td>
<td>$pπ^0(51.57 \pm 0.30%)$</td>
<td>Λγ(100%)</td>
</tr>
<tr>
<td></td>
<td>$nπ^0(35.8 \pm 0.5%)$</td>
<td>$nπ^+(48.31 \pm 0.30%)$</td>
<td></td>
</tr>
</tbody>
</table>

2.2 Accelerator and tagged photon system

In this experiment, a tagged photon with the energy region of 0.8-1.1 GeV was used at LNS-Tohoku. Here, the accelerator and the tagged photon system are explained.

2.2.1 LINAC

At LNS-Tohoku, a 300-MeV electron linear accelerator (LINAC) was built in 1967 and had provided a high-intensity pulsed beam for many purposes. LINAC worked as just an injector in our experiment. Although the maximum energy of LINAC is 300 MeV, the energy for the injection into the STB-ring is normally optimized to 150 MeV or 200 MeV.

2.2.2 STB-ring

A 1.2 GeV booster synchrotron (STretcher Booster, STB-ring) was constructed for the experiment of nuclear and hadron physics in 1996. Figure 2.1 shows the schematic view of the second experimental hall at LNS-Tohoku. There are two modes of the operation of STB-ring as follows,

- a pulsed beam from LINAC is stretched to a quasi-continuous beam,
- a beam energy from LINAC is boosted up to 1.2 GeV and the beam is stored in the ring.
2.2. ACCELERATOR AND TAGGED PHOTON SYSTEM

In our experiment, STB-ring was operated in the latter mode.

After an electron beam is injected to STB-ring from LINAC, its energy is boosted up to 1.2 GeV in 1.2 seconds. The beam is kept for 40 seconds in the ring and then dumped away by decreasing the electric current for the bending magnets. This cycle is continued as one spill. The interval between spills is changed by the beam time period from 7 seconds to 15 seconds due to the electric power of LNS-Tohoku.

![Schematic view of the second experimental hall at LNS-Tohoku. NKS2 is presented on the right-hand side of the figure.](image)

**Figure 2.1:** Schematic view of the second experimental hall at LNS-Tohoku. NKS2 is presented on the right-hand side of the figure.

2.2.3 BM4 STB tagging system

A tagged photon beam line is constructed around BM4 which is one of bending magnets of STB-ring. The photon beam is generated via bremsstrahlung and analyzed by the internal tagging system which is called as STB-Tagger [95]. It consists of an 11 μm carbon string radiator, an analyzing magnet (BM4) against a recoiled electron, and a plastic scintillator array. The plastic scintillator array consists of fifty scintillation counters (TagF) and twelve scintillation counters (TagB). TagF is located at the front of this array and TagB is aligned as backup counters. Figure 2.2 displays the schematic view of STB-Tagger.

After electrons are boosted up at STB-ring, the radiator is inserted on the trajectory of electron beam and the photon is generated into NKS2 via bremsstrahlung. Although the number of electrons in the ring decreases, the intensity of photon beam is controlled to be constant by moving the radiator between the flat top. The scattered electron is bended by BM4 and detected by TagF and TagB. The photon energy is determined by the hit segment
on TagF which is employed as a position detector. The energy calibration of tagged photons is explained in Sec. 3.2.3. The tagger counters are exposed under the environment with the huge backgrounds, because they are located near the circulating electron beam. Therefore, the coincidence between TagF and TagB is required to reject backgrounds which have different trajectories from that of the scattered electron on the radiator. In the coincidence logic, one TagB counter corresponds to four TagF counters. The trigger logic in detail is described in Sec. 2.6.1. The analysis is explained in Sec. 3.2.3.

The energy range of the tagged photons is from 0.8 to 1.1 GeV with the circulating electron beam energy of 1.2 GeV. The STB-Tagger system can provide the photon beam with a uniform intensity by controlling the velocity of the radiator. The beam intensity was adjusted to about 5-6 mA so that the rate of the summed TagF hits was about 1.5-2.0 MHz. The time of the flat top could be changed to 41 seconds from 20 seconds for the higher duty factor in December 2006. The duty factor was typically modified to 85% in NKS2 from 60% in NKS. The typical beam cycle is shown in Fig. 2.3.

The number of signals for each TagF counter are recorded by scalers to estimate the number of photons bombarded on the target. This analysis is described in Sec. 3.7.1.

The typical beam condition is summarized in Table 3.7.

### 2.3 Beam line setup

On the beam line a collimator, a dipole magnet (Sweep Magnet) and a vacuum chamber are located at the upstream of the target. A beam profile monitor (BPM) and a lead glass Čerenkov counter are located at the downstream of the target.
2.3. BEAM LINE SETUP

Figure 2.3: Typical beam cycle at this experimental period. The intensity of the circulating beam current was typically adjusted to 5 mA and the duty factor was typically 85%. The circulating beam current in STB-ring decreases by bombarding at the radiator.

Table 2.3: Typical beam condition. The circulating beam current, the flat top and the duty factor are typical values. The intensity of the photon beam is the average for the experimental period.

<table>
<thead>
<tr>
<th>circulating beam current</th>
<th>5 mA</th>
</tr>
</thead>
<tbody>
<tr>
<td>flat top</td>
<td>41 s</td>
</tr>
<tr>
<td>duty factor</td>
<td>85%</td>
</tr>
<tr>
<td>energy range of photon beam</td>
<td>0.8-1.1 GeV</td>
</tr>
<tr>
<td>accuracy</td>
<td>10 MeV</td>
</tr>
<tr>
<td>intensity of photon beam</td>
<td>1.6 MHz</td>
</tr>
</tbody>
</table>

The side view of the beam line is shown in Fig. 2.4.

2.3.1 Sweep magnet

In order to suppress the background events from the photon conversion in the event trigger, Sweep Magnet is located between the radiator and the target. A photon beam is irradiated on the target located at about 7 m downstream from the radiator. There are some materials on the path of the photon beam. They are the aluminum flange of the beam pipe (1 mm thickness), air and others. When a photon beam goes through the materials, some photons covert to the $e^+e^-$ pairs. It causes a serious background in the event trigger. Therefore, the $e^+e^-$ pairs should be removed before the target. Sweep Magnet, which is a dipole magnet with pentagonal-shaped poles, is used for this purpose. The flux density of the magnetic field is about 1.05 T with $\int B \cdot dl$ is typically about 0.5 T·m. The orbits of $e^+$ and $e^-$ created in the upstream are bent in the magnetic field. The $e^+$ and $e^-$ hit the lead blocks located at the downstream of the magnet. Therefore, the $e^+e^-$ pairs created in the upstream of Sweep Magnet does not reach the target and cannot make the event trigger.
CHAPTER 2. EXPERIMENTAL APPARATUS

The collimator, which is made of lead, is arranged in the upstream of Sweep Magnet to eliminate the beam halo. A block of the collimator is $100^W \times 108^H \times 50^T$ mm$^3$ and has a hole of 10 mm in diameter. Five blocks of the collimator are located on the beam line, then its total length is 250 mm.

The vacuum chamber is placed between the collimator and the target. By decreasing the total amount of materials, the photon conversion between Sweep Magnet and the target is suppressed.

2.3.2 Beam Profile Monitor (BPM)

The beam profile monitor (BPM) provides the beam position as the 2-dimensional information. In the period of the data taking, the beam position was monitored and recorded. It is located in the downstream of NKS2. BPM consists of 3 mm diced scintillating fiber counters, two trigger counters and the veto counter. Sixteen scintillation fibers are arranged on the horizontal and the vertical axis and are read out by two multianode photomultiplier tubes.

2.3.3 Lead glass Čerenkov counter

The lead glass Čerenkov counter is used for the estimation of the transmission rate of tagged photons. The calibration run using this counter was taken several times for the experimental period. Details of this analysis is discussed in Sec. 3.7.1.2. This counter having $150^W \times 150^H \times 300^T$ mm$^3$ volume, is located about 3.7 m downstream from the target. When the physical data was taken, the lead glass counter was put under the beam line to avoid being hit by the intense photon beam. When the data for the tagging efficiency was taken, it was arranged in the height of the beam line. In this case, the beam intensity was adjusted to be faint and the counting rate of the lead glass Čerenkov counter was a few hundred kHz at most.

Figure 2.4: Side view of the beam line setup. The lead glass Čerenkov counter located in the downstream was usually put under the beam line to avoid hitting the beam directly.
2.4 Neutral Kaon Spectrometer 2 (NKS2)

In order to investigate the $K^0$ photoproduction we have designed and constructed the Neutral Kaon Spectrometer (NKS2). It consists of a dipole magnet, two types of drift chambers, plastic scintillation hodoscopes and electron veto scintillation counters. Figure 2.5 displays the schematic view of NKS2. The configuration of the NKS2 detectors is symmetrical to the beam line.

The acceptance of this spectrometer covers the forward region, making it possible to measure much larger kinematical region for not only $K^0$ but also $\Lambda$ than that of the previous spectrometer, NKS.

![Figure 2.5: (a) Schematic view of NKS2. It consists of a dipole magnet (680 Cyclotron Magnet), two types of drift chambers (SDC, CDC), hodoscopes for the time of flight (IH, OH) and electron veto counters (EV). (b) Closeup in the center of NKS2.](image)

2.4.1 680 Magnet

The dipole magnet, which is called 680 Magnet, had been originally used as a cyclotron magnet at the Cyclotron Radioisotope Center, Tohoku University (CYRIC). The magnet has two circular-shaped poles with 1600 mm diameter. The gap size has been expanded to 680 mm by inserting four pieces of 234 mm thick iron blocks into the separable vertical return yoke in order to realize a large acceptance. The vertical holes (20 cm in diameter) in the poles and the yoke at the center of the pole face, originally used for the installation of ion sources, are utilized for the installation of the cryogenic target.

Table 2.4 shows the specification of 680 Magnet in the condition of NKS2 experiment. The flux density of magnetic field is 0.42 T at the center with 1000 A. The distribution of the
magnetic field for the data analysis is calculated by TOSCA program and the flux density is normalized using the peak position of the $K^0$ invariant mass. The magnetic field distributions at the mid-plane along the beam line ($z$-axis) and along the perpendicular to the beam line ($x$-axis) are shown in Fig. 2.6(a) and (b), respectively. Figure 2.6(c) and (d) display the $y$-axis dependence of the magnetic field along the $z$-axis and along the $x$-axis.

Table 2.4: Specification and the operated condition of 680 Cyclotron Magnet

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>radius of pole</td>
<td>800 mm</td>
</tr>
<tr>
<td>gap size</td>
<td>680 mm</td>
</tr>
<tr>
<td>number of pancake</td>
<td>10 pancakes</td>
</tr>
<tr>
<td>number of turns</td>
<td>25 turns/pancake</td>
</tr>
<tr>
<td>flux density of magnetic field</td>
<td>0.42 T</td>
</tr>
<tr>
<td>maximum current</td>
<td>1000 A</td>
</tr>
<tr>
<td>total weight</td>
<td>120 t</td>
</tr>
</tbody>
</table>

Figure 2.6: Magnetic field distributions of 680 Cyclotron Magnet at the mid-plane (a) along the beam line ($z$-axis) and (b) along the perpendicular to the beam line ($x$-axis). Dependence of the magnetic field on the $y$-axis (c) along the $z$-axis and (d) along the $x$-axis. These distributions are calculated by TOSCA program and the flux density is normalized using the peak position of the $K^0$ invariant mass.

2.4.2 Drift Chamber

NKS2 has two types of tracking detectors, Straw Drift Chamber (SDC) and Cylindrical Drift Chamber (CDC). They are located in the space between the top and bottom pole pieces of 680 Cyclotron Magnet, and they surround the target and IH.
Straw Drift Chamber (SDC)

SDC is installed inside CDC, which was designed in order to improve the vertex resolution. SDC is made of three layers. In the analysis, these three layers were treated as one group as described in Sec. 3.2.2. Figure 2.7(a) illustrates the bird’s eye view of SDC from the upstream. SDC covers from 100 mm to 155 mm in the radial direction and from −150 to 150 degrees in the angular range. The cell size in the forward region is small to decrease the counting rate per cell as shown in Fig. 2.7(b). The specification of SDC is summarized in Table 2.5.

The drift chamber is filled with a gas mixture of argon (50%) and ethane (50%) at the atmospheric pressure. The straw tubes are made of aluminized mylar films with 30 µm thickness. The positive voltage is supplied to sense wires. The sense wires made of gold-coated tungsten with 20 µm diameter are set with a tension of 50 gw.

Cylindrical Drift Chamber (CDC)

CDC consists of ten layers which are grouped into five groups by two layers. The layer number and group number are assigned from the inside including SDC. The schematic view of CDC is shown in Fig. 2.8. CDC covers from 200 mm to 800 mm in the radial direction and from −165 to 165 degrees in the angular range. The wires of 3rd group and 5th group in CDC are tilted against vertical axis and the typical stereo angle is 6.5 degrees. The shape of the cell is hexagonal and the maximum drift length is about 12 mm. The geometrical parameters are listed in Table 2.6.

The premixed gas of argon (50%) and ethane (50%) is used at the atmospheric pressure. In the operating condition of this experiment, the high voltage of −2.75 kV is supplied to the field wires and −1.375 kV to the shield wires. The sense wires are kept at the ground level.
Table 2.5: Specification of SDC

<table>
<thead>
<tr>
<th>group</th>
<th>layer</th>
<th>region</th>
<th>cell size</th>
<th>radius</th>
<th>sense wire</th>
<th>high voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>01 (X)</td>
<td>left, right</td>
<td>4.8</td>
<td>9.21</td>
<td>110</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td></td>
<td>forward</td>
<td>2.4</td>
<td>4.61</td>
<td>11</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>02 (X')</td>
<td>left, right</td>
<td>4.8</td>
<td>10.22</td>
<td>122</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td></td>
<td>forward</td>
<td>2.4</td>
<td>5.12(7.67)</td>
<td>10(2)</td>
<td>1.7(1.85)</td>
</tr>
<tr>
<td></td>
<td>03 (X)</td>
<td>left, right</td>
<td>4.8</td>
<td>11.34</td>
<td>135.3</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td></td>
<td>forward</td>
<td>2.4</td>
<td>5.67</td>
<td>11</td>
<td>1.7</td>
</tr>
</tbody>
</table>

TOTAL 200

The sense wires with 20 μm diameter (gold-coated tungsten) are set with a tension of 50 gw, while the field and shield wires with 100 μm diameter (gold-coated beryllium and copper) are set with a tension of 80 gw.

Figure 2.8: Schematic view of CDC. CDC is a drift chamber with the hexagonally-shaped cells and is made of ten layers.
### 2.4. NEUTRAL KAON SPECTROMETER 2 (NKS2)

#### 2.4.3 Time Of Flight (TOF) counters

TOF counters are two sets of plastic scintillation hodoscopes, i.e. Inner Hodoscope (IH) and Outer Hodoscope (OH). These counters are also used to make the event trigger. Each specification is listed in Table 2.7. The cross sections of the scintillators of IH and OH counters are trapezoidal to suppress the dead space.

### Inner Hodoscope (IH)

IH is used as the start counter for TOF measurements and serves as the time reference in the event trigger. IH consists of eight plastic scintillators, which are typically 120 mm length and 5 mm thickness, for each left and right arms except IH1. Only IH1 counters are arrayed in the up and down of the mid-plane. IH counters surround the target and are arranged from $-165$ degrees to $165$ degrees in the horizontal angle with the $2 \times 2$ cm$^2$ window in the downstream of the beam line as shown in Fig. 2.9(a).

The plastic scintillators of IH are made of Bicron BC420. The signal of IH is amplified at the single side using a photomultiplier (PMT) of 1 inch with fine mesh type dynodes developed for the use in a magnetic field (Hamamatsu Photonics K.K., H6152-01B). Although a gain of this PMT at 0.42 T is about 70% of that at no magnetic field. In the downstream of the target, the counting rate is very high for the photon conversion at the target materials. IH counters at the forward region are finely segmented to reduce the counting rate as seen in Fig. 2.9(b). The last two dynodes of the PMTs for them are connected to additional HV power supplies to avoid the decrease of the gain.

### Outer Hodoscope (OH)

OH is used as the stop counter and is one of the trigger counters. OH is segmented into 21 pieces for each left and right arms and in each arm has two types, which are horizontal type (OHH) and vertical type (OHV). The position of OH can be seen in Fig. 2.5. Moreover OHV arranged vertically has the different structures between the upstream and downstream of the target.
OHV1-8 counters, which have the scintillators with $748^H \times 150^W \times 20^T$ mm$^3$, arranged vertically in the downstream of the target as shown in Fig. 2.10(a). They consist eight pieces for each left and right arms (OHVL1-8, OHVR1-8). They are aligned on the circular arc with the radius of 1210 mm and are arranged from $\pm 1.4$ degrees to $\pm 59$ degrees in the horizontal angle.

OHH counters arranged horizontally consist of nine pieces for each left and right arm (OHHL1-9, OHHR1-9). The schematic view of OHH is shown in Fig. 2.11. The size of the scintillators is typically $160^L \times 80^W \times 20^T$ mm$^3$. The scintillators on the beam line are narrower width to avoid the high counting rate. OHH are located along the return yoke and are arranged from $\pm 55$ degrees to $\pm 125$ degrees in the horizontal angle.

OHV9-12 counters, which have the scintillators with $500^H \times 200^W \times 20^T$ mm$^3$, arranged vertically in the upstream of the target as shown in Fig. 2.10(b). They consist of four pieces for each left and right arm (OHVL9-12, OHVR9-12). They are located the circular pattern with the radius of 930 mm and are arranged from $\pm 113.8$ degrees to $\pm 163.4$ degrees in the horizontal angle.

PMTs of OH, which is typically H1161 or H7195 made by Hamamatsu Photonics K.K., is covered by the shield tubes made by iron to avoid the magnetic field. PMTs for OHVR10-12 have to be placed near the coils of the magnet to avoid the contact with the power cables of the magnet. Thus fine mesh type PMTs (Hamamatsu Photonics K.K., R5924-70) were employed for them.

### 2.4.4 Electron Veto counter (EV)

To suppress the background event from the photon conversion in the trigger level, Electron Veto counters (EV), which are plastic scintillation counters, are installed on the horizontal plane.
2.4. NEUTRAL KAON SPECTROMETER 2 (NKS2)

Figure 2.10: Schematic view of OHV arranged vertically (a) in the upstream of the target (OHV1-8) and (b) in the downstream (OHV9-12). OHV1-8(a) consists 8 pieces for each left and right arms, while OHV9-12(b) consists 4 pieces. The red plus marks(+) are the center of NKS2.

Figure 2.11: Schematic view of OHHL. OHHR was installed at the position of the symmetry to the $yz$-plane. OHH arranged horizontally consists of nine pieces for each left and right arm. The red plus mark(+) is the center of NKS2.
### CHAPTER 2. EXPERIMENTAL APPARATUS

Table 2.7: List of TOF counters. Each detector has the left (L) and right (R) components.

<table>
<thead>
<tr>
<th>ID</th>
<th>Size</th>
<th>Radius from Center</th>
<th>Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>IH</td>
<td>[mm]</td>
<td>[mm]</td>
<td>[deg.]</td>
</tr>
<tr>
<td>IH1</td>
<td>$66^H \times 24.55^W \times 5^T$</td>
<td>81</td>
<td>$(-9^L + 9^R)$</td>
</tr>
<tr>
<td>IH2</td>
<td>$160^H \times 16.30^W \times 5^T$</td>
<td>81</td>
<td>$\pm 9 - 21$</td>
</tr>
<tr>
<td>IH3</td>
<td>$160^H \times 32.95^W \times 5^T$</td>
<td>81</td>
<td>$\pm 21 - 45$</td>
</tr>
<tr>
<td>IH4</td>
<td>$160^H \times 32.95^W \times 5^T$</td>
<td>81</td>
<td>$\pm 45 - 69$</td>
</tr>
<tr>
<td>IH5</td>
<td>$160^H \times 32.95^W \times 5^T$</td>
<td>81</td>
<td>$\pm 69 - 93$</td>
</tr>
<tr>
<td>IH6</td>
<td>$160^H \times 32.95^W \times 5^T$</td>
<td>81</td>
<td>$\pm 93 - 117$</td>
</tr>
<tr>
<td>IH7</td>
<td>$160^H \times 32.95^W \times 5^T$</td>
<td>81</td>
<td>$\pm 117 - 141$</td>
</tr>
<tr>
<td>IH8</td>
<td>$160^H \times 32.95^W \times 5^T$</td>
<td>81</td>
<td>$\pm 141 - 165$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>OHV</th>
<th>Size</th>
<th>Radius from Center</th>
<th>Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>OHV1</td>
<td>$748^H \times 150^W \times 20^T$</td>
<td>1210</td>
<td>$\pm 1.4 - 8.6$</td>
</tr>
<tr>
<td>OHV2</td>
<td>$748^H \times 150^W \times 20^T$</td>
<td>1210</td>
<td>$\pm 8.6 - 15.8$</td>
</tr>
<tr>
<td>OHV3</td>
<td>$748^H \times 150^W \times 20^T$</td>
<td>1210</td>
<td>$\pm 15.8 - 23.0$</td>
</tr>
<tr>
<td>OHV4</td>
<td>$748^H \times 150^W \times 20^T$</td>
<td>1210</td>
<td>$\pm 23.0 - 30.2$</td>
</tr>
<tr>
<td>OHV5</td>
<td>$748^H \times 150^W \times 20^T$</td>
<td>1210</td>
<td>$\pm 30.2 - 37.4$</td>
</tr>
<tr>
<td>OHV6</td>
<td>$748^H \times 150^W \times 20^T$</td>
<td>1210</td>
<td>$\pm 37.4 - 44.6$</td>
</tr>
<tr>
<td>OHV7</td>
<td>$748^H \times 150^W \times 20^T$</td>
<td>1210</td>
<td>$\pm 44.6 - 51.8$</td>
</tr>
<tr>
<td>OHV8</td>
<td>$748^H \times 150^W \times 20^T$</td>
<td>1210</td>
<td>$\pm 51.8 - 59.0$</td>
</tr>
<tr>
<td>OHV9</td>
<td>$500^H \times 200^W \times 20^T$</td>
<td>930</td>
<td>$\pm 113.8 - 126.2$</td>
</tr>
<tr>
<td>OHV10</td>
<td>$500^H \times 200^W \times 20^T$</td>
<td>930</td>
<td>$\pm 126.2 - 138.6$</td>
</tr>
<tr>
<td>OHV11</td>
<td>$500^H \times 200^W \times 20^T$</td>
<td>930</td>
<td>$\pm 138.6 - 151.0$</td>
</tr>
<tr>
<td>OHV12</td>
<td>$500^H \times 200^W \times 20^T$</td>
<td>930</td>
<td>$\pm 151.0 - 163.4$</td>
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</table>

<table>
<thead>
<tr>
<th>OHH</th>
<th>Size</th>
<th>$x$</th>
<th>$y$</th>
<th>$z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>OHH1</td>
<td>$1600^H \times 82.5^W \times 20^T$</td>
<td>$\pm 1150$</td>
<td>302.5</td>
<td>0</td>
</tr>
<tr>
<td>OHH2</td>
<td>$1600^L \times 80^W \times 20^T$</td>
<td>$\pm 1150$</td>
<td>222.5</td>
<td>0</td>
</tr>
<tr>
<td>OHH3</td>
<td>$1600^L \times 80^W \times 20^T$</td>
<td>$\pm 1150$</td>
<td>142.5</td>
<td>0</td>
</tr>
<tr>
<td>OHH4</td>
<td>$1600^L \times 80^W \times 20^T$</td>
<td>$\pm 1150$</td>
<td>62.5</td>
<td>0</td>
</tr>
<tr>
<td>OHH5</td>
<td>$1600^L \times 45^W \times 20^T$</td>
<td>$\pm 1150$</td>
<td>0.0</td>
<td>0</td>
</tr>
<tr>
<td>OHH6</td>
<td>$1600^L \times 80^W \times 20^T$</td>
<td>$\pm 1150$</td>
<td>$-62.5$</td>
<td>0</td>
</tr>
<tr>
<td>OHH7</td>
<td>$1600^L \times 80^W \times 20^T$</td>
<td>$\pm 1150$</td>
<td>$-142.5$</td>
<td>0</td>
</tr>
<tr>
<td>OHH8</td>
<td>$1600^L \times 80^W \times 20^T$</td>
<td>$\pm 1150$</td>
<td>$-222.5$</td>
<td>0</td>
</tr>
<tr>
<td>OHH9</td>
<td>$1600^L \times 82.5^W \times 20^T$</td>
<td>$\pm 1150$</td>
<td>$-302.5$</td>
<td>0</td>
</tr>
</tbody>
</table>

† Only IH1 have the up and down components.

In the event trigger of this experiment, only EVL4 and EVR4 aligned in the upstream of the target were used. The positions of EVL4 and EVR4 can be confirmed in Fig. 2.5. Table 2.8 shows the specification of EV.

The accidental kill rate by EV is discussed in Sec. 3.7.5
2.5. LIQUID DEUTERIUM TARGET

The deuteron, contains one proton and one neutron, are used as the neutron target frequently in order to investigate the elementary process of kaon photoproductions.

In this experiment, the deuterium of the liquid phase was chosen in order to increase the density compared to the gaseous one and to decrease the density uniformity to the solid one. The target system, which was able to control the liquefaction of deuterium and kept the liquid state, was adapted to NKS2 system. This system could be controlled remotely by Lawgiver program running on a Linux machine in the experimental hall. During this experiment, this system was operated and the state of the liquid deuterium was monitored in the counting room via network. The temperature around a liquid deuterium and the pressure of the residual gas were monitored and recorded during the experiment to estimate the density. The density of the liquid deuterium could be estimated with small ambiguities.

2.5.1 Liquid deuterium target system

NKS2 was designed to be able to install the target at the center. If a target with the cryostat like as the liquid deuterium is used, the cryostat should be installed from the vertical holes with an inner diameter of 120 mm at the center of the yoke and the pole of 680 Cyclotron Magnet avoid the physical interferences as shown in Fig. 2.5. The cryostat was fixed in the lifter. When the liquid deuterium target was used, the target cell in the CFRP (carbon fiber reinforced plastic) pipe was put to the beam line to adjust the height by the lifter. The design of the target system with the cryostat is shown in Fig. 2.12.

The inside of the cryostat was pumped by the turbo molecular pump (Oerlikon Leybold Vacuum GmBH, Turbovac TMP151) as the main pump and by the dry scroll pump (Edwards ltd., XDS5) as back pump.

At the top of the cryostat, 2-Stage Gifford-McMahon refrigerator (Sumitomo Heavy Industries, ltd., SRD-208B) was placed. At the second stage of the refrigerator, an oxygen-free copper rod was attached to extend the stage to the center of NKS2 near the target cell. The refrigeration power of the first stage was also used to cool the thermal shield made of aluminum alloy. Two heat exchangers, a condenser and a re-condenser, were located at the end of the copper rod. The re-condenser worked to liquefy the evaporated deuterium from the cell. The deuterium was liquefied at the condenser and then dropped into the target cell.

<table>
<thead>
<tr>
<th>ID</th>
<th>Size</th>
<th>Position</th>
<th></th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>x</td>
<td>y</td>
<td>z</td>
<td></td>
</tr>
<tr>
<td>EV1</td>
<td>$750^L \times 50^W \times 10^T$</td>
<td>$\pm 35$</td>
<td>0</td>
<td>130</td>
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<td>EV2</td>
<td>$750^L \times 50^W \times 10^T$</td>
<td>$\pm 80$</td>
<td>0</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>EV3</td>
<td>$1250^L \times 50^W \times 5^T$</td>
<td>$\pm 60$</td>
<td>0</td>
<td>$-100$</td>
<td></td>
</tr>
<tr>
<td>EV4</td>
<td>$600^L \times 150^W \times 10^T$</td>
<td>$\pm 11.5$</td>
<td>0</td>
<td>$-51$</td>
<td></td>
</tr>
</tbody>
</table>
2.5.2 Temperature and pressure sensors

Three temperature sensors were attached in the cryostat. Six pressure monitors were set in the gas pipe lines.

Three temperature sensors were called the sensor A, B and C. The sensor C of a Cernox resistance sensor (Lake Shore Cryotronics, Inc., CX-1050) measured directly the temperature of the liquid deuterium in the target cell for the calculation of the density. Furthermore, The sensor B of a Carbon-Glass sensor (CGR-1-500) for the measurement of the liquid deuterium between the target cell and re-condenser parts were used. On the other hand, the sensor A of an other Cernox resistance sensor (CX-1030) was attached in the condenser and re-condenser parts with a 50 W heater (HTR-50). The temperature was controlled by feeding back the measured value by the sensor A to the heater.

The pressure of the deuterium gas in the duct was measured by an absolute pressure sensor (Copal Electronics Corp., PA-830-102A). Also, the five sensors (Copal Electronics Corp., PG-35-102R) were used for the opening and closing confirmation in valves.

On the other hand, The condition of the vacuum in the cryostat was measured by the vacuum gauge (Pfieffer Vacuum Technology AG, PKR251).

These values were monitored and recorded on the data taking. The temperature of the
2.5. LIQUID DEUTERIUM TARGET

liquid deuterium (sensor C) was kept to be about 19 K and the pressure of the residual gas was about 50 kPa. The density of the liquid deuterium target was evaluated from this temperature and this pressure. The density was estimated to be $0.174 \pm 0.001 \, \text{g/cm}^3$ typically. Details for the temperature and the pressure are explained in Table 3.11 as Sec. 3.7.2.

2.5.3 Target cell

The liquid deuterium is accumulated in the cell as shown in Fig. 2.13(a). The shell of this cell is made of aluminum with 1 mm$^T$ and the windows on the beam line are polymide films (Ube Industries, Ltd., UPILEX-S) with 75 $\mu$m$^T$ in order to reduce the materials. The offset of 15 mm from the center of NKS2 to the upstream is set as illustrated in Fig. 2.13(b). Therefore, the decay volume described in Sec. 3.3.3 are expanded to increase the yields of $K^0$ and $\Lambda$. The ring made of aluminum covers on the films to strengthen the pressure resistance. The inner diameter of the film region on the target cell is 40 mm. It is determined from the beam size of about 5 mm in rms and the fluctuation of the beam spot of about 4 mm.

When the liquid deuterium is accumulated in the target cell, the films of the target expanded by the pressure. The expansion of the target is about 1.65 mm at the center of the target cell from the measurement at normal temperature. The effective thickness was estimated to be $31.9 \pm 0.8 \, \text{mm}$ using the Monte-Carlo simulation as discussed in Sec. 3.7.2.

The target cell is installed in the vacuum chamber with cylindrical shape made of CFRP with 1.5 mm$^T$. This cylinder has two windows wrapping by the UPILEX-S films with 75 $\mu$m$^T$ on the beam line. Ten layers of the super insulators with 6 $\mu$m$^T$ and Two ones of the aluminized mylars with 50 $\mu$m$^T$ are inserted in the CFRP for the shield of the thermal radiation.

![Diagram of target cell](image)

Figure 2.13: (a) Size and the shape of the target cell. (b) and (c) Position of the target cell in the vacuum chamber. The offset of 15 mm from the center of NKS2 to the upstream was set to increase the yields of $K^0$ and $\Lambda$. 
2.6 Trigger logic and data acquisition (DAQ) system

In this section, the electronics for each detector and the trigger logic of this experiment are explained. Moreover, a programmable logic module, which is called Tohoku Universal Logic module (TUL-8040), is introduced. Finally, the data acquisition system is described.

2.6.1 Electronics

In this section, the electronics for each detector are described. Figures 2.14 and 2.15 show the electronics for each detector.

The charges of the analog signals of hodoscopes were read out by TKO 32ch ADC modules, which gate width was set to 100 nsec and dynamic range is 1000 pC. The timings of discriminated signals of hodoscopes by leading edge discriminators were read out by TKO HR TDC modules, which time resolution (least significant bit: LSB) is about 0.025 nsec per channel and dynamic range is 100 nsec. Time resolutions of each channel were calibrated using the TDC calibrator (RIS-0300) made by Fuji Diamond International Co., Ltd.

The signals of the drift chambers were amplified and discriminated by GNA-060 of a kind of Amplifier-Shaper-Discriminator (ASD) boards attached on the endplate of them. GNA-060 is made by Gnomes Design Co., Ltd. with SONY CXA3183Q chips, which integration time is 16 nsec. Table 2.9 shows the specification of ASD board. The digital signals with LVDS went to the resistances for the impedance matching, which is called pull-down resistance. Then the signals were read out by ATLAS Muon TDC modules (AMT) which time resolution (LSB) was set to be about 0.78 nsec per channel and dynamic range was 1 μsec. Time resolution of AMT was also calibrated channel by channel using the TDC calibrator (RIS-0300).

Table 2.9: Specification of ASD

<table>
<thead>
<tr>
<th>parameter</th>
<th>specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>gain of preamplifier</td>
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</tr>
<tr>
<td>integration time</td>
<td>16 nsec</td>
</tr>
<tr>
<td>feedback resistor</td>
<td>16 kΩ</td>
</tr>
<tr>
<td>gain of main-amplifier</td>
<td>7</td>
</tr>
<tr>
<td>input impedance</td>
<td>80 Ω</td>
</tr>
<tr>
<td>output impedance</td>
<td>open-emitter</td>
</tr>
<tr>
<td>comparator</td>
<td>LVDS output</td>
</tr>
</tbody>
</table>

2.6.2 Trigger

In this section, the trigger logics are described. Figure 2.16 shows the trigger logics for the normal run and the tagger calibration run.

For the physics runs, the event trigger was made by the photon beam side and the spectrometer side. The requirement of the beam side for the event trigger was made by the tagger counters. If a scattering electron by the radiator hits some tagger counter, a photon in the energy range from 0.8 to 1.1 GeV should be generated in principle. In fact the signals which had the coincidence between TagF and TagB were used for the suppression of the background. The requirement of the spectrometer side was that the event had more two charge particles. It
Figure 2.14: Logics of the trigger detectors. The trigger was made by tagger system, IH, OH and EV. Actually, the signals of only EV4 went to the logical sum (FANIN/FANOUT) of EV.

Figure 2.15: Logic of the drift chambers. The signals of the drift chambers were amplified and discriminated by ASD with 16 nsec integral time and were read out by AMT.
means that the more two than hits \( (N \geq 2) \) were required for each IH and OH. The majority logics were made using the TUL-8040 modules (Sec. 2.6.3). The signals of EV were used to reject the events of the photon conversion in the upstream of the target.

In addition, the spill gate, which opened in the motion of the radiator, was used for the rejection of the event that originated from the radiator.

For the calibration of taggers, only the tagger signals were used to make the event trigger. This trigger means that there is no bias from the condition of NKS2 side.

![Trigger for the production run](image)

![Trigger for the tagger calibration run](image)

Figure 2.16: Trigger logics of NKS2. The trigger for the production run were made by the requirement of the beam and the spectrometer. The that for the tagger calibration were made by only signals of the tagger.

### 2.6.3 Tohoku Universal Logic module (TUL-8040)

In the trigger logics, a programmable logic module, which is called Tohoku Universal Logic module (TUL-8040), was used. TUL is a VME module for an universal logic with 80 inputs and 40 outputs into a FPGA (Field Programmable Gate Array) chip of ALTERA APEX 20K series. The programs to be downloaded to TUL-8040 are developed with Quartus2 software using Verilog HDL. In this experiment, five TUL-8040 modules were used in total.

Two TUL-8040 modules made the mean timer for OH. As described in Sec. 2.4.3, The signals of OH were read out from two PMTs of each side, which means that the top and the bottom sides in OHV and the upstream and the downstream sides in OHH. Each discriminated signal of a OH counter was input to the TUL-8040 modules. The mean time signals of each signal by a OH counter were output.

Other two modules made a majority logic for IH and OH. The discriminated signals of IH by the constant-fraction discriminators (CFD) were input to the TUL-8040 module programed the majority logic. When the number of the input signals was more than one and more than two \( (N_{OH} \geq 1 \text{ and } N_{OH} \geq 2) \) each signal was output, respectively. The mean timer signals
of OH were input to the other module programmed as the majority logic. This majority logic output the signals which correspond to the multiplicity of more than one, two, three and four ($N_{OH} \geq 1$, $N_{OH} \geq 2$, $N_{OH} \geq 3$ and $N_{OH} \geq 4$).

The other one was used for the event matching between two Personal Computers (PC) for the data taking. It is called the bit counters. The bit counter output 4 bit signals in event by event. Two PCs recorded these 4 bit signals for the confirmation of the synchronization of each event.

### 2.6.4 Data acquisition system

Data were taken using two Personal Computers (PC) which had separated roles for the signals from hodoscopes and from the drift chambers. In each PC, UNIDAQ on Linux was used as a data acquisition system. The 4 bit signals explained above were collected by each PC and were used for the confirmation of the synchronization of each event in offline analysis. Figure 2.17 shows the schematic view of the data acquisition system.

To record the signals of hodoscopes, a TKO system, a VME system and a CAMAC system were used. All signals of hodoscopes were digitized by ADC and TDC modules of TKO. The digitized data were collected via a memory module (SMP) in the VME crate. The SMP has a dual memory and exchanged the role storing and reading event by event to reduce the dead time. If a LAM signal was occurred by the accept of the interrupt signal from the CAMAC module, the digitized data were read out from the SMP to the PC via a SBS Technologies Model 620-3. The scaler data were collected via a CC-77000 module of the CAMAC system during the off-spill period.

All signals of drift chambers were digitized by AMT of VME. Two VME crates were used but were controlled as one unit by SBS Technologies Model 418. It was a VME repeater module and could extend a VMEbus back-plane from one chassis to a second chassis. In the same way of the hodoscope system, a LAM signal made via the interrupt register of the CAMAC module and the digitized data were read out to the PC via a SBS Technologies Model 620-3.

### 2.7 Data summary

Data were taken for the deuteron target in November, December 2006 and in January, June 2007. The experimental periods were about 2 weeks in November, December 2006 and in January 2007, and were about 3 weeks in June 2007. Table 2.10 shows the summary of the production data taking in NKS2. The duty factor was about 85% with 40 seconds of the flat top time. The intensity of the tagged photon beam was from 1.5 to 2.0 MHz. The data set in November 2006 was taken the different trigger condition of veto counters, it is not discussed in this thesis.

The tagging efficiency runs were used for the estimation of the transmission rate of the tagged photons on the target position. The tagger analysis runs were for the estimation of the ratio between the scaler value of TagF and the effective number of the generated photons in the analysis. The calibration runs are summarized in Table 2.11.
Figure 2.17: Data acquisition system of NKS2

Table 2.10: Data summary of the production runs for each period

<table>
<thead>
<tr>
<th>period</th>
<th>#spill</th>
<th>photon (CAMAC Scaler)</th>
<th>beam intensity (summed TagF hits)</th>
</tr>
</thead>
<tbody>
<tr>
<td>December</td>
<td>11410</td>
<td>7.97825×10^{11}</td>
<td>1.465 MHz</td>
</tr>
<tr>
<td>January</td>
<td>8312</td>
<td>7.62361×10^{11}</td>
<td>1.929 MHz</td>
</tr>
<tr>
<td>June</td>
<td>21736</td>
<td>1.69369×10^{12}</td>
<td>1.653 MHz</td>
</tr>
</tbody>
</table>

Table 2.11: Data summary of the calibration runs of the tagging efficiency and the tagger analysis efficiency

<table>
<thead>
<tr>
<th>period</th>
<th>#spill</th>
<th>photon (CAMAC Scaler)</th>
<th>calibration run</th>
</tr>
</thead>
<tbody>
<tr>
<td>December</td>
<td>83</td>
<td>7.52633×10^{7}</td>
<td>tagging efficiency</td>
</tr>
<tr>
<td></td>
<td>766</td>
<td>6.09574×10^{10}</td>
<td>tagger analysis efficiency</td>
</tr>
<tr>
<td>January</td>
<td>40</td>
<td>7.80364×10^{7}</td>
<td>tagging efficiency</td>
</tr>
<tr>
<td></td>
<td>574</td>
<td>5.89591×10^{10}</td>
<td>tagger analysis efficiency</td>
</tr>
<tr>
<td>June</td>
<td>272</td>
<td>1.15398×10^{8}</td>
<td>tagging efficiency</td>
</tr>
<tr>
<td></td>
<td>1411</td>
<td>1.24739×10^{11}</td>
<td>tagger analysis efficiency</td>
</tr>
</tbody>
</table>
Chapter 3

Analysis

3.1 Analysis overview

In this chapter, the procedure of the data analysis is described. The goal of this analysis is to obtain the differential cross section of the inclusive $K^0$ and $\Lambda$ photoproduction. A flow chart of the data analysis is described in Fig. 3.1.

Firstly, the raw data are converted into times, energy deposits and drift lengths by each detector using the input parameters. These parameters by each detector and each run are...
prepared. Secondly, the tracking using the hit information of the drift chambers is performed. Thirdly, the hits of IH and OH corresponding to the track are searched and the flight time of the track is obtained. Also, the velocity of the particle is calculated from the flight time and the flight length reconstructed from the track. The kind of particles is identified using the correlation between the velocity and the momentum. Fourthly, if more than two tracks can be reconstructed, the vertex point of two tracks is reconstructed. Additionally, the invariant mass distribution is obtained using the information of momenta at the vertex point and kinds of particles. and \( K^0 \) or \( \Lambda \) events are distinguished from other hadronic events. Lastly, the yield is corrected using the acceptance, the number of photons, the number of targets and various efficiencies. Then the cross section is derived.

### 3.2 Calibration and performance of detectors

#### 3.2.1 Calibration of TOF counters

As described in Sec. 2.4.3, TOF counters consist of IH and OH in NKS2. In this analysis, the time of flight can be determined using the time difference between IH and OH.

In the circuit of this experiment, the analog pulse of the hodoscope was discriminated by the leading edge discriminator. Therefore, the difference of the height of analog pulse makes the shift of the observed time from TDC data, which is called time-walk. This time-walk was corrected for each PMT by the following equation,

\[
t_{\text{corr}} = t_{\text{raw}} - \frac{p_0}{|dE - p_1|} + p_2,
\]

where \( dE, t_{\text{raw}} \) and \( t_{\text{corr}} \) are an energy deposit from the ADC data, a raw and a corrected time from the TDC data, respectively. And \( p_0, p_1 \) and \( p_2 \) are the fitting parameters, respectively. Figure 3.2 shows the typical effect of a time-walk correction. The time before the time-walk correction delays with decreasing the energy deposit. On the other hand, the time after correction is not depend on the energy deposit. The time difference between each IH, each TagF and TagB were adjusted to be zero by each run using the \( e^+e^- \) events.

The times passed IH and TagB are converted using Eq. (3.1), because the signals of those detectors were read from the one side. Figure 3.3 shows the time difference between IHL and IHR for the \( e^+e^- \) events and Fig. 3.4 is that between IH and tagger. The peaks around 0 ns in these figures indicate the true coincidence. Meanwhile the others with 2 ns bunch in Fig. 3.4 are the accidental coincidence made by the RF signals of the accelerator. The distribution of Fig. 3.3 was fitted by the Gaussian and its width was obtained to be about 240 ps (\( \sigma \)). Therefore, the time resolution of each IH was estimated to be 170 ps (\( \sigma \)). The time resolution in Fig. 3.4 was obtained to be about 320 ps (\( \sigma \)). Therefore, it is consistent with the estimation using the detector resolutions of IH and Tagger (310 ps : described in Sec. 3.2.3).

A OH signal was read from the both sides of the scintillator. The time and the hit position through OH are described as follows:

\[
t_0 = t_{\text{top}} - t_{\text{bottom}}\frac{2}{2},
\]

\[
y = t_{\text{top}} - t_{\text{bottom}}\frac{2}{2} \cdot v,
\]
3.2. CALIBRATION AND PERFORMANCE OF DETECTORS

Figure 3.2: Typical effect of a time-walk correction (IHL2). The left figure is the correlation between a time and an energy deposit before the correction. The right figure shows that after the correction. The time dependence on the energy deposit is smaller after the correction.

Figure 3.3: Time difference between IHL and IHR for the $e^+e^-$ events. The resolution is 230 ps ($\sigma$).

where $t_{\text{top\,corr}}$ and $t_{\text{bottom\,corr}}$ are the corrected times by the signals of PMTs on the top and bottom sides for OHV (the upstream and downstream sides for OHH), respectively. The time passed OH, $t_0$, can be determined by an average of $t_{\text{top\,corr}}$ and $t_{\text{bottom\,corr}}$. The $y$ is the hit position in OH and the $v$ is the propagation velocity of light passing through a plastic scintillator.

The time of flight is determined by the difference between the passed time of corresponding IH and OH. The offset of OH was determined by the photon conversion events using the following equation,

$$\text{TOF}_{\text{resolution}} = \frac{fl}{c} - ft,$$  

(3.4)

where $fl$ is the flight length from the tracking and the velocity of electrons and positrons is assumed to be that of light, $c$. The $ft$ is the flight time calculated from the time difference between IH and OH. In the case of the photon conversion, the $\text{TOF}_{\text{resolution}}$ of Eq. (3.4) has to be zero and the offset of OH was adjusted as such. Figure 3.5 shows the time difference
Figure 3.4: Time difference between IH and tagger for the $e^+e^-$ events. The periodic structure of 2 ns is caused by the beam bunch. The resolution is 320 ps ($\sigma$).

Figure 3.5: Resolutions of the time of flight. It was estimated using Eq. (3.4) after having selected the events of an electron and a positron which are assumed to have light velocities.

### 3.2.2 Calibration of drift chambers

#### 3.2.2.1 Clustering and pre-selection

In the present analysis, the following procedures are carried out before the tracking to select candidates of good hits to reduce analysis time caused by huge combination.

Firstly, the event which has the larger multiplicity of hits by a layer for the drift chambers (MLH) was rejected. Figure 3.6 shows the MLH distributions in each period. The cut condition which the MLH was under twenty was applied in this analysis.

Secondly, the combinations making the cluster were searched. As described in Sec. 2.4.2, three layers of SDC make one group. The five groups in CDC are composed of three groups by axial and two groups by stereo. Figure 3.7 shows the conditions making the cluster. When the wires hatched by red region have a hit, the green hatched regions represent the cell with
3.2. CALIBRATION AND PERFORMANCE OF DETECTORS

Figure 3.6: Maximum multiplicity of layer hits for the drift chambers. The number of entries for January and June is normalized to that of December.

possibility for making the cluster. The cluster combined the neighboring hits between layers of the same group in CDC. The condition making the cluster in SDC was that the angles of the hitting wires in each layer were within 8 degrees. If neighboring hits do not exist, the cluster from one hit, which size is one, was made. The angle of cluster was defined as an average of the angle of the constructed wires in the $zx$-plane.

Figure 3.7: Conditions making the cluster for SDC and CDC. The left figure is the condition for SDC and the right is for CDC. When the wires hatched by red region have a hit, the green hatched regions represent the cell with possibility for making the cluster.

The candidate of the trajectory of a track was made by the combinations of the clusters by each group. Here, the maximum number of clusters is four in order to consider of only axial layer. To suppress of the analysis time, the condition for the combinations was applied as the follows,

- $|\phi_{SDC1} - \phi_{CDC2}| < 25^\circ$,
- $|\phi_{CDC2} - \phi_{CDC4}| < 35^\circ$,
- $|\phi_{CDC4} - \phi_{CDC6}| < 25^\circ$,
where $\phi_i$ is the angle of the cluster of the group $i$ in the horizontal plane. The combinations of the clusters by each group were searched from the outer group. If there is no corresponding cluster in the next group, the combination of the clusters were searched in the after next group. These condition was applied as the follows,

- $|\phi_{SDC1} - \phi_{CDC4}| < 55^\circ$,
- $|\phi_{CDC2} - \phi_{CDC6}| < 45^\circ$.

Additionally, when the candidate matched the following requirement, the tracking was performed.

- at least 3 clusters,
- at least 6 hits in total.

The tracking is performed to the candidate which approves these requirements at the next stage.

### 3.2.2.2 TDC calibration

Only the timing of rising edges of discriminated signals was recorded by the multihit TDCs for the drift chambers. Therefore, the drift length was calculated by the TDC data. The electrons ionized by the charged particle drift to the sense wire by the electric field. The drift velocities of SDC and CDC are not linear, because the electric field of the drift region cannot secure the region of a constant velocity. Firstly, the drift velocity was assumed to be a constant velocity of 50 $\mu$m/ns which is a typical value of the drift velocity by the premix gas of Ar:C$_2$H$_6$=50:50. Secondly, the correlation between the drift length and the drift time is obtained from the tracking using the assumed velocity. Here, the drift length is defined as the distance between the trajectory and the wire, and assumed to be 2nd and 3rd polynomials function of the drift time for SDC and CDC, respectively. Next, the correlation is obtained from the re-tracking using the velocity from this function. The process of the tracking and the obtaining drift velocity is iterated until the $\chi^2$ settles. Figure 3.8 shows the correlation between the drift length and the drift time.

![Figure 3.8: Correlation between the drift time and the drift length. The right and left figures show the correlation of layer03 in SDC and that of layer09 in CDC, respectively.](image-url)
3.2.2.3 Tracking

The tracking was performed against the candidate of the hits. The trajectory of a charged particle in the magnetic field was calculated by the cubic spline interpolation method [96]. Firstly, the fitting was carried out in the mid-plane using vertical components of the magnetic field and axial layers by the least $\chi^2$ method. At this stage of the analysis, bad tracks with $\chi^2 > 300$ were rejected. The candidates of the vertical position through a stereo layer by the track were evaluated using the position and stereo angle of the stereo layer. Then, the vertical tracking was carried out using stereo layers by the least $\chi^2$ method. Here, the information of the tracking with large $\chi^2$ ($\chi^2 > 10$) was not used. Then, the vertical information was obtained from the hit position of OH and the target. This is performed after the search of IH and OH hits corresponding to the track as described below.

Secondly, IH and OH hits corresponding to the track were searched. The IH segment corresponding to the track was searched by simple extrapolation of a track using the spline function. Basically the nearest IH in the mid-plane was adopted. However, when the trajectory was through two IH as shown in Fig. 3.9, one with the short distance from the innermost hit of DC in the track was selected. Also the segment 1 of IH, which position is the same in the mid-plane, was selected using the vertical information. In case of OH, the trajectory was extrapolated from the outermost hit of DC in the track to OH by 4th Runge-Kutta method. The nearest OH in the mid-plane were searched and labeled to the track.

Finally, after these processes were done, the re-fitting was performed off the mid-plane using vertical components of the magnetic field obtained by the previous fitting. In the latter analysis, a robust fitting method by J. W. Tukey [97] was used, which is a method to find a plausible track in consideration of weights for hits. The weights were changed according to the residual calculated in the previous fitting. In the fitting, the horizontal component of the momentum by the track was parametrized and obtained from the tracking result. The vertical tracking was also carried out.

![Figure 3.9: Example for the search of IH hit when the trajectory was through two IH. In this case, IHL8 is nearest hit but IHR3 is selected with the short distance from the innermost hit of DC in the track was selected.](image)
3.2.2.4 \( t_0 \) correction and re-tracking

The \( t_0 \) correction and the re-tracking are carried out using the particle identification as described after this. The velocity of particle was obtained after the search for IH and OH corresponding to the track. The difference of the velocity made the shift of the drift time in the first tracking. Because the arrival time to the cell of the drift chamber depends on the velocity of the particle. In addition, the raw data of TDC have the trigger information. These dependence of the velocity was corrected for each particle by the following equation,

\[
t_{\text{corr}} = t_{\text{raw}} - (t_{IH} + \frac{f l_i}{v} - \frac{y_i}{c})
\]

where \( t_{raw} \) and \( t_{corr} \) are a raw and corrected time from the TDC data of the drift chamber and \( t_{IH} \) are a corrected time of IH. The \( fl_i \) and \( v \) are the flight length from IH position to layer \( i \) and velocity of particle, respectively. The \( fl_i/v \) represents the flight time to layer \( i \). The \( y_i \) and \( c \) are the vertical hit position of layer \( i \) and the light velocity. Here the propagation time of a signal in the wire was corrected. Figure 3.10 shows the effect of this correction. The tracking was performed using the corrected time once again.

Figure 3.10: Effect of the time correction of layer12 in CDC. The left figure shows the correlation before the correction and the right shows the correlation after one.

3.2.2.5 Position resolution and layer efficiency

The resolution was estimated using the difference between the drift lengths predicted by the fitting and calculated from the drift time, which is called the residual. The inclusive and exclusive residuals mean the distance from the tracking with the aiming layer and without that, respectively. However, these widths are immediately not corresponding to the intrinsic resolution of the drift chamber. Because these residual distributions include the accuracy of the estimated trajectory and the fitting routine. It can be confirmed that the residual distribution do not become to zero if the intrinsic resolution is assumed to be zero in the simulation. In the present analysis, the intrinsic resolution was estimated from the comparison between the intrinsic resolution and the two kinds of residuals. The comparison of the residual distributions
between the simulation and experiment was shown in Fig. 3.11. The right figures show the correlation between the intrinsic resolution and the two kinds of residual of the simulation by each layer and the right figures represent the residual distributions of the experiment. The intrinsic resolutions of SDC and CDC except for layer12 and layer13 were estimated to be 150 µm and 200 µm (σ), respectively. The resolutions of the outer layers (layer12 and layer13) have the discrepancy in the estimated values predicted by the inclusive residual and by the exclusive. It is caused by the difference between the magnetic field on the experimental condition and the simulation. The resolutions of layer12 and layer13 including the accuracy of the magnetic field were estimated to be 260 µm (σ).

Figure 3.11: Comparison of the residual between simulation and experiment. The upper and lower figures show the inclusive and exclusive residuals, respectively. The comparison between intrinsic resolution and the residuals is shown in the left figures. The right figures represent the result of the experiment.

Figure 3.12 shows the layer efficiencies of the drift chambers for layer01, layer04, layer08 and layer12. The efficiency of each layer kept more than 95% over the region except for the forward. The one or two wires of the forward region on the beam line had too high counting rate (a few hundred kHz) and were masked in the data taking.

### 3.2.3 Calibration of tagger

#### 3.2.3.1 Energy calibration with Sweep magnet

The experiment for the energy calibration using the photon conversion was carried out in 2000. In this experiment, the momenta of $e^+e^-$ from the pair creation in a copper converter of 0.9 mmφ were measured using Sweep magnet and the drift chamber which consists of $uu', xx', vv'$ planes with the hexagonal shaped cells. The typical strength of the magnetic field on Sweep
magnet was 0.78867 Tesla with 220 A. The distribution of the magnetic field was calculated by TOSCA program and the absolute value was normalized by the measured values using NMR. The trajectories from the fitting were trace back by Runge-Kutta method and determined its momenta. The photon energy was calculated by

$$E_\gamma = \sqrt{|p_e^+|^2 + m_e^2} + \sqrt{|p_e^-|^2 + m_e^2}$$

(3.6)

where $E_\gamma$, $p_e^+$ and $p_e^-$ are the energy of photon, determined momenta of the electron and the positron, respectively. And $m_e$ is the mass of an electron or a positron. This calibration using the photon conversion gives the results as follows,

$$E_\gamma = 1.1053 - 0.0067 \times i \text{[GeV]}$$

(3.7)

where $i$ is the segment number of TagF.

### 3.2.3.2 Energy calibration using hadronic productions

The photon energy using hadronic productions in this experimental period indicated the different results from that with Sweep magnet. There are two prominent types of this calibration as follows, which all particles of final state was measured or not.

**Method.(1)** not all particles of the final state were measured

**Method.(2)** all particles of the final state were measured.

**Method.(1)**

When all particles are not captured, the calibration using the $\gamma d \rightarrow p\pi^- X$ process is explained for example. Here, the photon bombed on the deuteron target, and $p$ and $\pi^-$ were measured. The conservations of the energy and the momentum are derived as follows,

$$E_\gamma + E_d = E_p + E_{\pi^-} + E_X,$$

(3.8)

$$E_\gamma = p_p + p_{\pi^-} + p_X,$$

(3.9)

where $E_\gamma$, $E_d$, $E_p$, $E_{\pi^-}$ and $E_X$ are the energies of each particle ($\gamma$, $d$, $p$, $\pi^-$ and $X$), respectively. $E_\gamma$, $p_p$, $p_{\pi^-}$ and $p_X$ are the momenta of each particle, respectively.
If this reaction is the single pion production, \( X \) should be a proton. Then the relation between the energy and the momentum of \( X \) are the following under this assumption,

\[
E_X^2 = m_p^2 + |p_X|^2,
\]

(3.10)

where \( m_p \) is the mass of the proton. The photon energy is expressed as follows by Eqs. (3.8), (3.9) and (3.10),

\[
E_\gamma = \frac{m_p^2 + |p_p + p_{\pi^-}|^2 - (E_d - E_p - E_{\pi^-})^2}{2(E_d - E_p - E_{\pi^-} + (p_p + p_{\pi^-}) \cdot \hat{e}_\gamma)}
\]

(3.11)

\[
E_\gamma = \frac{m_p^2 + |p_p + p_{\pi^-}|^2 - (m_d - E_p - E_{\pi^-})^2}{2(m_d - E_p - E_{\pi^-} + (p_p + p_{\pi^-}) \cdot \hat{e}_\gamma)},
\]

(3.12)

where \( \hat{e}_\gamma \) is the unit vector parallel to the direction of the photon, which means \( z \)-axis of NKS2 coordinate system. The energy of the deuteron(\( E_d \)) is equal to the mass(\( m_d \)) in order that the deuteron is at rest. Similarly, the photon energies are expressed as follows using the \( \gamma d \rightarrow p\pi^+\pi^-X \) or the \( \gamma d \rightarrow p\pi^+\pi^-\pi^-X \) processes,

\[
E_\gamma = \frac{m_n^2 + |p_p + p_{\pi^+} + p_{\pi^-}|^2 - (m_d - E_p - E_{\pi^+} - E_{\pi^-})^2}{2(m_d - E_p - E_{\pi^+} - E_{\pi^-} + (p_p + p_{\pi^+} + p_{\pi^-}) \cdot \hat{e}_\gamma)},
\]

(3.13)

\[
E_\gamma = \frac{m_p^2 + |p_p + p_{\pi^+} + p_{\pi^-} + p_{\pi^0(1)} + p_{\pi^0(2)}|^2 - (m_d - E_p - E_{\pi^+} - E_{\pi^-(1)} - E_{\pi^-(2)})^2}{2(m_d - E_p - E_{\pi^+} - E_{\pi^-(1)} - E_{\pi^-(2)} + (p_p + p_{\pi^+} + p_{\pi^-(1)} + p_{\pi^-(2)}) \cdot \hat{e}_\gamma)},
\]

(3.14)

where \( E \)'s, \( p \)'s and \( m \)'s are the energies, momenta and masses with the additional characters for the kind of particles, respectively. Eq. (3.13) is used in the case of the double pion photoproduction and the mass of the missing particle is assume to be that of the neutron. Eq. (3.14) means the three pion photoproduction, and the missing particle is assume to be the proton. The difference of the calibrated energies between with Sweep magnet and using hadronic process is shown in the left panel of Fig. 3.13.

**Method.(2)**

It is the case that all particles of the final state were measured. It means the non quasi-free process of the single pion photoproduction \( (\gamma d \rightarrow pp\pi^-) \) was occurred on the deuteron. In this case, the energy of photon is derived as the follows,

\[
E_\gamma = |p_{p(1)} + p_{p(2)} + p_{\pi^-}|.
\]

(3.15)

The difference of the calibrated energies between with Sweep magnet and this method is shown in the right panel of Fig. 3.13. Also, the validity of this analysis was confirmed by using the Monte-Carlo simulation based on Geant4 and can be appeared in the figure.

The accuracy of this method, especially the magnetic field, could be confirmed using the \( \gamma d \rightarrow pp\pi^- \) process. The conservation of the energy is derived by the follows,

\[
E_\gamma + E_d = E_{p(1)} + E_{p(2)} + E_{\pi^-}.
\]

(3.16)

Therefore the mass of the deuteron is calculated by the momenta of the final state as the following,

\[
m_d = E_{p(1)} + E_{p(2)} + E_{\pi^-} - |p_{p(1)} + p_{p(2)} + p_{\pi^-}|.
\]

(3.17)
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This equation does not include the photon energy. When the momenta of the final state shifts, it is reflected in the mass of the deuteron. The difference of the deuteron mass between Eq. (3.17) and the PDG value is shown in Fig. 3.14 (left). The right figure shows how the calculated deuteron mass by Eq. (3.17) shifts on the inaccurate scaling of the magnetic field. The strength of the magnetic field scaled against that in the Monte-Carlo simulation was used in the analysis. Then the correlation between the scaling factor and the calculated deuteron mass was obtained. This correlation is represented as the black line in the figure. Since the mass deference was shifted to be $-3.8 \text{ MeV/c}$ (right figure), it indicates that the inaccurate scaling of the magnetic field is under 1%.

Figure 3.13: Energy calibration of tagger. This figure is represented the difference of the calibrated energy between using photon conversion and the hadronic production.

Figure 3.14: Accuracy of measured momenta by the $\gamma d \rightarrow pp\pi^-$ process. This left figure represents the difference of the the deuteron mass between Eq. (3.17) and the PDG value. This line is estimated using the Monte-Carlo simulation. The mass deference was shifted to be $-3.8 \text{ MeV/c}$ (right figure). It indicates that the discrepancy of the strength of the magnetic field scaling is about 0.6%.

The energy calibrations using hadronic productions indicates the consistent results. In this analysis, this calibrated values by the hadronic productions were adopted. The systematic errors was estimated to be $<10 \text{ MeV}$ from Fig. 3.14.
3.2.3.3 Clustering and time gate

The photon energy and the number of photons bombed on the target are determined using tagging counters. In the tagger analysis, the events of the accidental coincidence between TagF and TagB and the events which have two and more photons at the same beam bunch were rejected. Additionally, misidentifies one event to two are removed.

Firstly, the time of TagB was corrected using the ADC and the TDC data by Eq. (3.1). On the other hand, the only TDC data against TagF were recorded in order to be lighten the data size. Therefore, time information of TagF was obtained from TDC data. The relative timing among each TagF segment and TagB segment was adjusted to be zero. The upper figure of Fig. 3.15 shows the time difference between TagF and TagB. The gate of time was set within 2 ns in order to reject the accidental coincidence between TagF and TagB.

Secondly, TagF hits were collected in the cluster. The cluster with the size of two is identified as two hits of neighbor segments on TagF within 2 ns. When there is no hit in the neighbor segments, one hit make the cluster with the size of one. These clusters are defined as "TagH". The segment and the energy of TagH are taken as an average of them by the associated TagF hits and the time was taken as that of TagB. The lower figure of Fig. 3.15 shows the time difference between TagF and TagF making other cluster. The events which is separated more than 3 ns are required. The periodic structure of 2 ns can be confirmed as same as Fig. 3.4.

Figure 3.15: Time gate of tagger. The upper figure shows the time difference between TagF and TagB. The gate of time is set within 2 ns. The lower figure shows the time difference between TagF and TagF making other cluster. The events which is separated more than 3 ns are required. The periodic structure of 2 ns can be confirmed as same as Fig. 3.4.

(1) two and more photons generated in the same beam bunch
(2) a low energy photon without the tagger region hit a tagger

(3) other process

There is the process(1) as the same amount as the bunch structure confirmed on the lower panel of Fig. 3.15. Which photon involved the reaction cannot be distinguished. Therefore, the events on the process(1) were not used in the analysis. Its effect is included by the tagger analysis efficiency. To explain process(2), Figure 3.16 is displayed. It shows the time difference between a hit of TagH and other one with the segment of TagH separated more than 4. The difference between the upper and the lower figures is the rate of the summed TagF hits. When this peak around zero appeared, a low energy photon (about 0.5 GeV) outside of the energy region of the tagger was generated according to ADC data of the lead glass Čerenkov counter. A similar phenomenon was being reported by the other group using the other beam line at LNS-Tohoku. According the report [98],

The electrons with the large momentum distribution are scattered by the radiator. Though a part of these electrons is detected by the tagger, the most part have the higher momentum than the energy region of the tagger. Some electrons without the energy region of the tagger might collide the flange of the vacuum chamber of the beam line and change the trajectories. There is a certain probability that the tagger has the hit without the corresponding energy.

It seems that a similar phenomenon took part in this peak. It is the cause of the misidentification of the number of photons and events. However its effect was estimated to be small for this analysis. Because the photon energy confirmed this phenomenon was under the threshold of the $\gamma n \rightarrow K^0 \Lambda$ reaction. On the other hand, the peak around zero on Fig. 3.15(lower) cannot be explained quantitatively by only process(1) and (2). It is clear that the other process(3) exists for the main component of this peak. To analyze the tendency of this peak, it appeared between certain specific segments. Additionally the time difference was sharper than the resolution of TagF. Though it is not possible to conclude, it seems that there is crosstalk. This effect is considered in the tagger analysis efficiency.

Thirdly, it was required that the time difference between TagF and TagF making other cluster is away from 3 ns. The cluster filling this requirement is defined as 'TagSH'. It is means the photon which can be used in the analysis was generated.

The histogram of Fig. 3.16 was fitted by 3 Gaussian. and the time resolution was 440 ps ($\sigma$). Then the resolution of tagger was about $440/\sqrt{2}\sim310$ ps.

3.3 Event selection

3.3.1 Good track selection

A good track was selected from the number of hit layers in the track and the $\chi^2$ distribution. Moreover the residual distribution between the center of the hit hodoscope and the trajectory is used.

The track that the number of hit layers in tracks is more than 6 at least is required. The $\chi^2$ distributions of each track were shown in Fig. 3.17. The $\chi^2 < 8$ is required as a good track.

The residual distribution between the center of the hit hodoscope and the trajectory is expressed as the distance in the horizontal plane. Figure 3.18 shows the residual distributions
3.3. EVENT SELECTION

Figure 3.16: Time difference between a hit of TagH and other one. The resolution was 440 ps ($\sigma$).

Figure 3.17: $\chi^2$ distributions of the pion and the proton. The left and right figure shows that for the pion and the proton, respectively.

for each hodoscope. The distributions of these figures of IH and OHV represent the half widths of hodoscopes. The widths of IH are described in Table 2.7 and the typical width is 3.3 cm. The cut condition of 1.4 cm, 0.9 cm and 2.0 cm for the residual distributions are required as the segment number 1, 2 and others, respectively. The widths of the upstream and downstream of OHV are 15 cm and 20 cm, respectively. And these distributions are required within 10 cm and 12.5 cm, which mean the half widths plus 2.5 cm, as a good track. The distributions for OHH, which installed on the horizontal plane, are made by the resolutions of two PMTs by both sides. The cut condition within 10 cm for OHH is required.
3.3.2 Particle identification

The particle identification was determined by the mass and the charge of the particle. The mass \( (m) \) is calculated by the correlation between the momentum \((p)\) and the velocity \((\beta)\) as follows,

\[
m^2 = p^2 \left( \frac{1}{\beta^2} - 1 \right),
\]

The sign of the charge is determined using the bending direction in the magnetic field.

Figure 3.19 shows the scatter plot between the momentum and the inverse of velocity of particles after applying the opening angle selection in order to reject the photon conversion events. The sign of the longitudinal axis expresses the charge of the particle. The separation of the particle identification for the pion is defined as,

\[
\beta^{-1} > 0.5,
\]

\[
|p| < \frac{0.144}{\beta^{-1} - 0.2} - 0.08 \quad (for \ 0.5 \leq \beta^{-1} < 2),
\]

\[-0.5 < m^2 < 0.25 \ [(GeV/c^2)^2],
\]

that for the proton is,

\[
0.5 < m^2 < 1.8 \ [(GeV/c^2)^2],
\]
and that for the deuteron is,

\[ 1.8 < m^2 < 5.5 \quad [(\text{GeV}/c^2)^2], \] (3.21)

The regions for the particle identification of the pion, the proton and the deuteron are shown in Fig. 3.19. The red lines represent the pion region by Eq. (3.19) and the blue is the proton region by Eq. (3.20).

Figure 3.19: Correlation between the momentum and the inverse velocity. The sign of the momentum represents the charge of the particle. The events which the opening angle on the vertex, \( \eta \), is \(-0.9 < \cos \eta < 0.8\) are selected to remove \( e^+e^- \) events.

Figure 3.20 shows the power of the particle identification. In the upper figures, the peaks of the pion and the proton are shown in this distribution of inverse velocity for each momentum and were fitted using a Gaussian distribution. The vertical lines with red and blue color represent the boundaries of the region for each particle. The lower figure is the distance between the peaks of the fit results and the boundaries of PID, which point the high mass and the low one for the pion and the proton, respectively. The unit of the distance is \( \sigma \) of the fit results. The maximum momentum of the pion and the proton from kaon photoproductions in this energy region is about 0.7 GeV/c and 1.0 GeV/c, respectively. Therefore, the distance is away more than two sigma.

### 3.3.3 Vertex distribution

The vertex point was defined as the center of the closest points by two tracks.

Firstly, the trajectory is extrapolated by the Runge-Kutta method from the innermost hit layer. Secondly, the combination of the closest points is searched from the extrapolated points. Finally, the precise closest points using the Runge-Kutta method of the smaller step size are
Figure 3.20: Power of the particle identification. The upper figure shows the distribution of the inverse velocity for each momentum. The peaks of the pion and the proton were fitted using the Gaussian distributions of red line and blue, respectively. The lower figure shows the distance using $\sigma$ unit between the peaks of the fit result and the boundaries of PID, which point high mass and low one against the pion and the proton, respectively.

searched and the vertex point is reconstructed. Figure 3.21 shows the schematic view of this method. Figure 3.22 shows the closest distance of two tracks. The closest distance within 5 cm is required as a good combination.

Figure 3.23 shows the distribution of the vertex point. The scatter plot is one projected to the horizontal plane. In this figure, the materials around the target are shown. It is recognized that the almost events generated at the liquid deuterium target and some events came from the UPILEX-S films of the vacuum chamber and the films for the shield of the heat radiation.

Here, it is confirmed that the position of the target cell is different from the design value. The cryostat of the target system has the long arm for the installation from the top of 680 Cyclotron Magnet. Therefore, it seems that the target was not installed with high accuracy. Figure 3.24 shows the differential vertex point of $z$-direction. The position of the target cell was estimated to be $z = -0.8$ cm. The offset of the target cell was determined using the fit result.
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Figure 3.21: Method of the vertex reconstruction from two tracks. In the first step, the closest points of each track which are calculated by the Runge-Kutta method are selected. In the next step, the precise closest points are searched for the red region using the Runge-Kutta method of the smaller step size.

Figure 3.22: Closest distance Distributions between two tracks of $\pi^+\pi^-$ events. The events which the opening angle($\eta$) is $-0.9 < \cos \eta < 0.8$ are selected.

by two Gaussian distributions. Table 3.9 shows the position of the target cell for each period. The difference of each period is under 1 mm.

Table 3.1: Position of the target cell for each period.

<table>
<thead>
<tr>
<th>Period</th>
<th>$z$ (upstream) [cm]</th>
<th>$z$ (downstream) [cm]</th>
<th>center [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>December</td>
<td>$-2.43 \pm 0.01$</td>
<td>$0.78 \pm 0.01$</td>
<td>$-0.82 \pm 0.02$</td>
</tr>
<tr>
<td>January</td>
<td>$-2.48 \pm 0.01$</td>
<td>$0.75 \pm 0.01$</td>
<td>$-0.86 \pm 0.02$</td>
</tr>
<tr>
<td>June</td>
<td>$-2.53 \pm 0.01$</td>
<td>$0.72 \pm 0.01$</td>
<td>$-0.91 \pm 0.02$</td>
</tr>
</tbody>
</table>

Figure 3.25 shows the vertex difference required using three track events. The vertex is
CHAPTER 3. ANALYSIS

Figure 3.23: Vertex distributions of $\pi^+\pi^-$ events. The upper figure is the scatter plot on the $zx$-plane. The target position is drawn as green region and the decay volume is defined by red region. The lowers are the vertex distributions on each axis.

Figure 3.24: Differential vertex point of the $z$-direction. The offset of the target cell was determined using the fit result by two Gaussian distributions for the lower figure.
3.3. **EVENT SELECTION**

searched using the arbitrarily-chosen two tracks among three and three combinations of the vertex are obtained. The vertex difference means the difference of those vertices. This difference should be zero in the infinite high resolution. The vertex resolution in the horizontal plane in rms was $1.5/\sqrt{2} \sim 1.1$ mm with the halo of $0.5/\sqrt{2} \sim 3.5$ mm. Furthermore, the resolution of $y$-component was about $6.0/\sqrt{2} \sim 4.2$ mm.

Figure 3.25: Vertex difference of 3 track events. Three combinations of the vertex is obtained using the arbitrarily-chosen two tracks among three. The vertex difference means the difference of those vertexes. The vertex resolution in the horizontal and vertical plane was about $1.5/\sqrt{2} \sim 1.1$ mm and $6.0/\sqrt{2} \sim 4.2$ mm, respectively.

### 3.3.4 Kinematics selection

#### 3.3.4.1 kinematics selection of the inclusive measurement

The reaction point cannot be decided accurately when the only $K^0$ or $\Lambda$ were measured. Because the life time of these particles have so long that these particles decay with the flight length of a few centimeter. Figure 3.26 shows the schematic view of the definition of the generated point. The decay length, $d_{len}$, and the generated point was derived as the follows,

\[
\text{dlen} = \frac{|p \cdot (dp - tp)|}{|p|},
\]

\[
gp - tp = \begin{cases} 
  dp - tp - d_{len} \cdot \frac{p}{|p|} & p \cdot (dp - gp) \geq 0 \\
  dp - tp + d_{len} \cdot \frac{p}{|p|} & p \cdot (dp - gp) < 0 
\end{cases}
\]
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where \( vp, gp \) and \( tp \) are the vertex point, the generated point and the target point, respectively. The following conditions are used in order to require the generation in the target.

\[
\begin{align*}
| (gp - tp) \cdot \hat{z} | & < 2.0 \text{ [cm]}, \\
| (gp - tp) \cdot \hat{x} | & < 2.0 \text{ [cm]},
\end{align*}
\]

where \( \hat{z} \) and \( \hat{x} \) are unit vector of z- and x-axis, respectively.

3.3.5 Opening angle selection

It was difficult to determine exactly the vertex point, when two particles go almost parallel to each other. Therefore, the events which the opening angle(\( \eta \)) is too large or too small were rejected. This selection also has the effect to remove \( e^+e^- \) events which were almost generated with the same direction of each other. The opening angle of \(-0.9 < \cos \eta_{\pi^+\pi^-} < 0.7 \) and \(-0.8 < \cos \eta_{\mu\pi^-} < 0.9 \) was applied for the inclusive \( K^0 \) and \( \Lambda \) measurement, respectively.

3.3.6 Missing mass selection

3.3.6.1 missing mass of the inclusive \( K^0 \) measurement

The electromagnetic interaction requires the conservation of strangeness number. When only \( K^0 \) is detected in the photon energy region of this experiment, the hyperon, especially \( \Lambda \) of the \( \gamma n \rightarrow K^0 \Lambda \) reaction, should be generated simultaneously.

However, only \( K^0 \) is detected, the missing mass cannot be determined exactly. Because the neutron on the deuteron has the Fermi momentum. Thus, the missing mass was calculated as the assumption of the rest nucleon in the inclusive measurement. The missing mass square for the inclusive \( K^0 \) measurement was defined as follows,

\[
m_{\gamma N \rightarrow \pi^+\pi^- X}^2 = (E_\gamma + m_N - E_{\pi^+\pi^-})^2 - |E_\gamma - p_{\pi^+\pi^-}|^2,
\]

where \( m_N \) and \( E_\gamma \) are the assumed nucleon mass, which is assumed to be 940 MeV/\( c^2 \) and the photon energy obtained by the tagger, respectively. The \( E_{\pi^+\pi^-} \) and \( p_{\pi^+\pi^-} \) are the energy and
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the momentum of the reconstructed particle. These are defined as

\[ E_{\pi^+\pi^-}^2 = m_{\pi^+\pi^-}^2 + |p_{\pi^+\pi^-}|^2, \]  
\[ p_{\pi^+\pi^-} = p_{\pi^+} + p_{\pi^-}, \]  

(3.31)

(3.32)

where \( p_{\pi^+} \) and \( p_{\pi^-} \) are the measured momenta of \( \pi^+ \) and \( \pi^- \) with an energy loss correction, respectively. And the \( m_{\pi^+\pi^-} \) is the invariant mass of \( \pi^+\pi^- \) described in next section.

The upper figure of Fig. 3.27 shows the missing mass square distributions of \( \gamma N \to \pi^+\pi^- X \). The black and red lines represent that without and with the \( \pi^+\pi^- \) invariant mass selection to require Eq. (3.38), respectively. The green one is simulation result of \( \gamma n \to K^0\Lambda \) reaction using the Monte-Carlo method. The following condition is required,

\[ m_{\gamma N \to \pi^+\pi^- X}^2 > 1 \text{[(GeV/c^2)^2]}, \]  

(3.29)

The effect of this selection was confirmed by the \( \pi^+\pi^- \) invariant mass distribution of the lower histogram in Fig. 3.27. The black and red lines represent that without and with the \( \gamma N \to \pi^+\pi^- X \) missing mass selection represented as Eq. (3.39), respectively. The efficiency of this selection was estimated to be 99.0\( \pm \)0.3\% from the Monte-Carlo simulation with the isotropic distribution at the center of mass system. In this analysis, this inefficiency was negligibly small.

3.3.6.2 missing mass of the inclusive \( \Lambda \) measurement

To the same way as the inclusive \( K^0 \) measurement, the missing mass square for the inclusive \( \Lambda \) measurement was define as follows,

\[ m_{\gamma N \to p\pi^- X}^2 = (E_\gamma + m_N - E_{p\pi^-})^2 - |E_\gamma - p_{p\pi^-}|^2. \]  

(3.30)

The upper histograms of Fig. 3.28 shows the missing mass square distributions of \( \gamma N \to p\pi^- X \). The black and red lines represent that without and with the \( p\pi^- \) invariant mass selection represented as Eq. (3.39). The green one is simulation result of \( \gamma n \to K^0\Lambda \) reaction. The following condition is required,

\[ m_{\gamma N \to p\pi^- X}^2 > 0 \text{[(GeV/c^2)^2]}, \]  

(3.33)

The effect of this selection was confirmed by the \( p\pi^- \) invariant mass distribution of the lower histogram in Fig. 3.28. The black and red lines represent that without and with the \( \gamma N \to p\pi^- X \) missing mass selection represented as Eq. (3.33), respectively. The efficiency of this selection was estimated to be 99.5\( \pm \)0.2\% using the Monte-Carlo simulation with the isotropic distribution at the center of mass system. In this analysis, this inefficiency was negligibly-small.
Figure 3.27: Missing mass distributions for $\pi^+\pi^-$ events. The upper figure is the $\gamma N \rightarrow \pi^+\pi^- X$ missing mass square distribution. The red line histogram is observed with the $\pi^+\pi^-$ invariant mass selection represented as Eq. (3.38) in order to select the $K^0$ events. The green one is simulation result of $\gamma n \rightarrow K^0\Lambda$ reaction. The lower figure is the $\pi^+\pi^-$ invariant mass distribution. The red line is that after the $\gamma N \rightarrow \pi^+\pi^- X$ missing mass selection represented as Eq. (3.29),

3.3.6.3 missing mass of exclusive $K^0\Lambda$ measurement

The missing mass distribution of $p\pi^-\pi^+\pi^-$ events was calculated by

$$m_{\gamma d \rightarrow p\pi^-\pi^+\pi^-X}^2 = (E_\gamma + M_d - E_{\pi^-} - E_{\pi^+})^2 - |E_\gamma - p_{\pi^-} - p_{\pi^+}|^2,$$

where $m_d$ is the mass of deuteron (1.875612 GeV/$c^2$) from the PDG value.

The missing mass distributions of the $\gamma d \rightarrow p\pi^-\pi^+\pi^-X$ event is shown in Fig. 3.29. The peak around 0.94 GeV/$c^2$ in the black line is made by the three-pions photoproduction on the boundary neutron. The red line histogram shows the $K^0\Lambda$ events for the the invariant mass selection represented as Eqs. (3.38) and (3.39).

The following condition is required.

$$|m_{\gamma d \rightarrow p\pi^-\pi^+\pi^-X} - m_p| < 50 \ [MeV/c^2].$$

The width of the mass gate corresponds to more than 3σ region. The inefficiencies by this selection is negligibly small.

3.3.7 Invariant mass distribution

The events of the $K^0$ production are identified by the $\pi^+\pi^-$ invariant mass distribution and these of the $\Lambda$ production are by that of the $p\pi^-$. The invariant mass was calculated from the
3.3. EVENT SELECTION

Figure 3.28: Missing mass distributions for $p\pi^-$ events. The upper figure is the $\gamma N \rightarrow p\pi^- X$ missing mass square. The red line histogram is observed with the $p\pi^-$ invariant mass selection represented as Eq. (3.39) in order to select the $\Lambda$ events. The green one is simulation result of $\gamma n \rightarrow K^0\Lambda$ reaction. The lower figure is the $p\pi^-$ invariant mass distribution. The red line is that after the $\gamma N \rightarrow p\pi^- X$ missing mass selection represented as Eq. (3.33).

Figure 3.29: Missing mass distributions for $p\pi^+\pi^-\pi^-$ events. The black and red lines are that to require the invariant mass selection represented as Eqs. (3.38) and (3.39).

measured momenta by

\[ m_{\pi^+\pi^-}^2 = \left( \sqrt{m_{\pi^+}^2 + \left| p_{\pi^+} \right|^2} + \sqrt{m_{\pi^-}^2 + \left| p_{\pi^-} \right|^2} \right)^2 - \left| p_{\pi^+} + p_{\pi^-} \right|^2, \]  

(3.36)

\[ m_{p\pi^-}^2 = \left( \sqrt{m_p^2 + \left| p_p \right|^2} + \sqrt{m_{\pi^-}^2 + \left| p_{\pi^-} \right|^2} \right)^2 - \left| p_p + p_{\pi^-} \right|^2, \]  

(3.37)
where $m_{\pi^+}$, $m_{\pi^-}$ and $m_p$ are the masses of the charged pion (0.13957018 GeV/$c^2$) and the proton (0.93827203 GeV/$c^2$) from the PDG value, respectively. And $p_{\pi^+}$, $p_{\pi^-}$ and $p_p$ are the measured momenta with an energy loss correction, respectively.

### 3.3.7.1 invariant mass of the inclusive $K^0$ measurement

Figure 3.30 shows the invariant mass distributions of $\pi^+\pi^-$ events. The cut condition is summarized in Table 3.2. The peak of $K^0$ mass is obtained around 0.5 GeV/$c^2$. The width in rms by a Gaussian fit is 5.24±0.34 MeV/$c^2$ for the photon energy from 0.90 to 1.00 GeV and 5.84±0.40 MeV/$c^2$ for the photon energy from 1.00 to 1.08 GeV. The following condition is required.

$$|m_{\pi^+\pi^-} - m_{K^0}| < 13 \text{ [MeV}/c^2],$$  \hspace{1cm} (3.38)

where $m_{K^0}$ is the mass of $K^0$ (0.497614 GeV/$c^2$) from the PDG value and $m_{\pi^+\pi^-}$ is the invariant mass calculated by Eq. (3.36). The efficiency of the $K^0$ invariant mass selection was estimated to be 98.0% and the systematic error was to be ±1.8%.

![Invariant Mass Distributions](image)

**Figure 3.30:** Invariant mass distributions of $\pi^+\pi^-$ events in the photon range from 0.80 to 0.90 GeV (upper), from 0.90 to 1.00 GeV (middle) and from 1.00 to 1.08 GeV (lower).

### 3.3.7.2 invariant mass of the inclusive $\Lambda$ measurement

Figure 3.31 shows the invariant mass distributions of $p\pi^-$ events. The cut condition is summarized in Table 3.2. The peak of $\Lambda$ mass is obtained around 1.115 GeV/$c^2$. The width in
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rms by a Gaussian fit is $2.06 \pm 0.05 \text{ MeV}/c^2$ for the photon energy from 0.90 to 1.00 GeV and $2.13 \pm 0.05 \text{ MeV}/c^2$ for the photon energy from 1.00 to 1.08 GeV. The following condition is required,

$$|m_{p\pi^-} - m_\Lambda| < 5 \text{ [MeV}/c^2],$$

(3.39)

where $m_\Lambda$ is the mass of $\Lambda$ (1.115683 GeV/$c^2$) from the PDG value and $m_{p\pi^-}$ is the invariant mass calculated by Eq. (3.37). The efficiency of the $\Lambda$ invariant mass selection was estimated to be 97.8% and the systematic error was to be $\pm 1.3\%$.

Figure 3.31: Invariant mass distributions of $p\pi^-$ events in the photon range from 0.80 to 0.90 GeV (upper), from 0.90 to 1.0 GeV (middle) and from 1.00 to 1.08 GeV (lower).

3.3.7.3 invariant mass of the exclusive $K^0\Lambda$ measurement

Invariant mass spectra for $p\pi^+\pi^-\pi^-$ events are shown in Fig. 3.32. The scatter plot (a) is the correlation between invariant mass distributions of $p\pi^-$ and $\pi^+\pi^-$. The $K^0$ peak was observed in the $\pi^+\pi^-$ distribution (b) with the $p\pi^-$ invariant mass selection of Eq. (3.39). The $\Lambda$ peak is shown in the the $p\pi^-$ invariant mass (c) with the $\pi^+\pi^-$ invariant mass selection of Eq. (3.38).

The cut condition of Eq. (3.38) for the $\pi^+\pi^-$ invariant mass and of Eq. (3.39) for the $p\pi^-$ one is required. The efficiencies of the these two invariant mass selections for the exclusive events was estimated to be 96.0% in total. And the systematic error was to be 3.1%.

3.3.8 Summary of event selection

The various event selections in the present analysis are summarized in Table 3.2. Additionally, the event selection that two decay particles make the event trigger was required in the inclusive
Figure 3.32: Invariant mass distributions for $p\pi^+\pi^−\pi^−$ events. The scatter plot(a) is the correlation between invariant mass distributions of $p\pi^−$ and $\pi^+\pi^−$. The histogram(b) and (c) is the $\pi^+\pi^−$ invariant mass to require Eq. (3.39). and the $p\pi^−$ invariant mass to require Eq. (3.38).

measurement. It means that $\pi^+$ hit the different segment of IH and OH than the segments through $\pi^−$ on the inclusive $K^0$ measurement. Because the discrepancy between the analysis of the experimental data and that of the simulated data for the acceptance is resolved.

Table 3.2: Summary of various event selections.

<table>
<thead>
<tr>
<th>Common selection (for $K^0$ inclusive, $\Lambda$ inclusive and $K^0\Lambda$ exclusive)</th>
<th>Timing selection</th>
<th>Number of hit layers in track</th>
<th>$\chi^2$ selection</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$\geq 6$</td>
<td>$\chi^2 \leq 8$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Selection for the inclusive measurement</th>
<th>$K^0$ inclusive</th>
<th>$\Lambda$ inclusive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generated point</td>
<td>$-0.9 &lt; \cos \eta_\pi^+\pi^- &lt; 0.7$</td>
<td>$-0.9 &lt; \cos \eta_{p\pi^-} &lt; 0.9$</td>
</tr>
<tr>
<td>Opening angle selection</td>
<td>$&lt; 5$</td>
<td>$&lt; 5$</td>
</tr>
<tr>
<td>Closest distance cut [cm]</td>
<td>$\circ$</td>
<td>$\circ$</td>
</tr>
<tr>
<td>Decay volume selection</td>
<td>$m_{\gamma N\rightarrow\pi^+\pi^-X^2} &gt; 1$</td>
<td>$m_{\gamma N\rightarrow p\pi^-X^2} &gt; 0$</td>
</tr>
<tr>
<td>Missing mass cut [(MeV/c$^2$)$^2$]</td>
<td>$</td>
<td>m_{K^0} - m_{\pi^+\pi^-}</td>
</tr>
<tr>
<td>Invariant mass cut [MeV/c$^2$]</td>
<td>$\circ$</td>
<td>$\circ$</td>
</tr>
</tbody>
</table>
3.4 Estimation of background

3.4.1 Background estimation of the inclusive $K^0$ measurement

Even after the requirement of all selections, the contributions of background exist. It can be confirmed from the $\pi^+\pi^-$ invariant mass distribution in Fig. 3.30. These contributions have to be estimated and need to be subtracted to extract the inclusive $d(\gamma, K^0)YN$ cross section.

The contributions to the background were assumed to come from the following two types:

B.G.(1) There was a reconstructed vertex outside the target for the finite resolution though $\pi^+\pi^-$ was generated in the target;

B.G.(2) It is for mis-combination between $\pi^+$ from the $K^0 \to \pi^+\pi^-$ decay and $\pi^-$ from the $\Lambda \to p\pi^-$ decay.

B.G.(1)

In the analysis for the the inclusive $K^0$ measurement, the events with the vertex in the decay volume were selected as described in Sec. 3.3.3. However, some other hadronic events have a vertex in the decay volume for the finite resolution.

The distributions of this background could be assumed to be the same as these of the events whose vertex point was reconstructed in the target region. Therefore, the distributions were estimated from the experimental data after the event selections except for the decay volume selection.

B.G.(2)

In the present analysis, the vertical component of the vertex resolution was not so good and then the accidental combination was not removed by the closest distance selection. Therefore, there is the mis-combination between $\pi^+$ from the $K^0 \to \pi^+\pi^-$ decay and $\pi^-$ from the $\Lambda \to p\pi^-$ decay. Sometimes, the vertex of the mis-combination indicates that the particle decays in the decay volume like Fig. 3.33.

The distribution of this background was estimated using the Monte-Carlo simulation based on Geant4. The distribution was simulated under the following condition,

- the intensity of the photon energy is flat in the tagger region.
- the excitation function of the $n(\gamma, K^0)\Lambda$ reaction linearly increases with the center of mass energy.
- the angular distribution is isotropic in the center of mass system.
- the neutron momentum in the deuteron is assumed to be Hulthén wave function.
- the reaction is quasi-free and the binding energy in the deuteron is negligible.

The contributions of these backgrounds were estimated using the fitting of the the invariant mass in the region from 0.35 GeV/$c^2$ to 1.00 GeV/$c^2$. The peak of the $K^0$ mass spectra was assumed to be a gaussian distribution and these backgrounds were only scaled. Figure 3.34 shows the results of the fitting. Table 3.3 shows the signal ($S$) to noise ($N$) ratios, $S/N$, to require the invariant mass selection of Eq. (3.38). The number of noises ($N$) is estimated using the fitting results of the invariant mass and the number of signals ($S$) indicates the rest number subtracting that of noise from that of events in the invariant mass of Eq. (3.38). The ratio was estimated to be 2.79 in the photon energy from 0.90 to 1.00 GeV and 2.10 from 1.00 to 1.08 GeV.
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Figure 3.33: Example of the background from the mis-combination. The $\pi^+$ from the $K^0 \rightarrow \pi^+\pi^-$ decay and the $\pi^-$ from the $\Lambda \rightarrow p\pi^-$ decay make the vertex in the decay volume.

Figure 3.34: Fitting results of the $\pi^+\pi^-$ invariant mass. The upper figure shows that in the photon energy from 0.90 GeV to 1.00 GeV and the lower one shows from 1.00 GeV to 1.08 GeV. The contribution of the background in the higher invariant mass than $K^0$ mass is mainly for the leakage of target events(B.G.(1)). And both background components(B.G.(1-2)) contribute in the $K^0$ mass region and the lower region.

Table 3.3: Signal to noise ratio ($S/N$) of the inclusive $K^0$ measurement for each region of photon energy in the invariant mass of Eq. (3.38).

<table>
<thead>
<tr>
<th>Photon Energy [GeV]</th>
<th>#Signals($S$)</th>
<th>#Noises($N$)</th>
<th>$S/N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.90 - 1.00</td>
<td>373 ± 25 ± 6</td>
<td>134 ± 12 ± 6</td>
<td>2.79 ± 0.27 ± 0.13</td>
</tr>
<tr>
<td>1.00 - 1.08</td>
<td>337 ± 26 ± 7</td>
<td>161 ± 13 ± 7</td>
<td>2.10 ± 0.19 ± 0.10</td>
</tr>
</tbody>
</table>
3.4.2 Background estimation of the inclusive $\Lambda$ measurement

The background contribution of the inclusive $\Lambda$ measurement is small after the event selection (seen in Fig. 3.31).

The distributions of the background were assumed to be these of the both side bands in the $p\pi^-$ invariant mass. The regions of the bands are defined as follows,

$$\text{Region.A} : |(m_{p\pi^-} - m_{\Lambda}) - 10| < 5 \ [\text{MeV}/c^2],$$

$$\text{Region.B} : |(m_{p\pi^-} - m_{\Lambda}) + 10| < 5 \ [\text{MeV}/c^2].$$

These distributions are scaled using the fitting results of the invariant mass. Meanwhile, the $\Lambda$ events of the skirt of the peak in the invariant mass exist in the both side bands. The amount of over subtractions was estimated and regulated by the feedback. Table 3.4 shows the scaling and the feedback factors for each region of the photon energy. The errors are estimated from the fitting ones.

Table 3.4: Scaling factors for two side backgrounds of the inclusive $\Lambda$ measurement.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.80 - 0.90</td>
<td>$(1.07 \pm 0.02) \times 0.5$</td>
<td>$(0.938 \pm 0.02) \times 0.5$</td>
<td>$1.00 \pm 0.01$</td>
</tr>
<tr>
<td>0.90 - 1.00</td>
<td>$(1.04 \pm 0.02) \times 0.5$</td>
<td>$(0.959 \pm 0.02) \times 0.5$</td>
<td>$1.02 \pm 0.01$</td>
</tr>
<tr>
<td>1.00 - 1.08</td>
<td>$(1.04 \pm 0.02) \times 0.5$</td>
<td>$(0.959 \pm 0.02) \times 0.5$</td>
<td>$1.02 \pm 0.01$</td>
</tr>
<tr>
<td>0.85 - 0.90</td>
<td>$(1.05 \pm 0.03) \times 0.5$</td>
<td>$(0.958 \pm 0.02) \times 0.5$</td>
<td>$1.01 \pm 0.01$</td>
</tr>
<tr>
<td>0.90 - 0.95</td>
<td>$(1.04 \pm 0.03) \times 0.5$</td>
<td>$(0.967 \pm 0.02) \times 0.5$</td>
<td>$1.02 \pm 0.01$</td>
</tr>
<tr>
<td>0.95 - 1.00</td>
<td>$(1.06 \pm 0.03) \times 0.5$</td>
<td>$(0.947 \pm 0.02) \times 0.5$</td>
<td>$1.02 \pm 0.01$</td>
</tr>
<tr>
<td>1.00 - 1.05</td>
<td>$(1.08 \pm 0.03) \times 0.5$</td>
<td>$(0.928 \pm 0.02) \times 0.5$</td>
<td>$1.02 \pm 0.01$</td>
</tr>
<tr>
<td>1.05 - 1.08</td>
<td>$(1.00 \pm 0.03) \times 0.5$</td>
<td>$(0.995 \pm 0.03) \times 0.5$</td>
<td>$1.03 \pm 0.01$</td>
</tr>
</tbody>
</table>

Table 3.5 shows $S/N$ ratios to require the invariant mass selection of Eq. (3.39). The number of noises ($N$) is estimated using the fitting results of the invariant mass by a gaussian and a linear function. To the same way as the inclusive $K^0$ measurement, the number of signals ($S$) is derived from that of events in the invariant mass of Eq. (3.39) subtracted by that of noise ($N$). The ratio was estimated to be 5.34, 9.30, 11.39 and 11.13 in the photon energy of 0.90-0.95 GeV, 0.95-1.00 GeV, 1.00-1.05 GeV and 1.05-1.08 GeV.

3.5 Event distribution

3.5.0.1 Event distribution of the inclusive $K^0$ measurement

Figure 3.37 shows the momentum and the angular distributions of the inclusive $K^0$ measurement in the photon energy ranges from 0.90 to 1.00 GeV and from 1.00 to 1.08 GeV. The event selections to obtain these distributions are described in Table 3.2. In these figures, the green squares and the blue triangles present the background contributions as discussed in Sec. 3.4.1. Figure 3.36 shows the momentum distributions of the inclusive $K^0$ measurement for each angle.
Table 3.5: Signal to noise ratio ($S/N$) of the inclusive $\Lambda$ measurement for each region of photon energy in the invariant mass of Eq. (3.39).

<table>
<thead>
<tr>
<th>Photon Energy [GeV]</th>
<th>#Signals(S)</th>
<th>#Noises(N)</th>
<th>S/N</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.85 - 0.90</td>
<td>152 ± 20</td>
<td>133 ± 12</td>
<td>1.14 ± 0.12 ± 0.07</td>
</tr>
<tr>
<td>0.90 - 0.95</td>
<td>673 ± 30</td>
<td>126 ± 11</td>
<td>5.34 ± 0.51 ± 0.27</td>
</tr>
<tr>
<td>0.95 - 1.00</td>
<td>1192 ± 38</td>
<td>128 ± 11</td>
<td>9.30 ± 0.86 ± 0.45</td>
</tr>
<tr>
<td>1.00 - 1.05</td>
<td>1310 ± 39</td>
<td>115 ± 11</td>
<td>11.39 ± 1.10 ± 0.56</td>
</tr>
<tr>
<td>1.05 - 1.08</td>
<td>1002 ± 34</td>
<td>90 ± 10</td>
<td>11.13 ± 1.22 ± 0.55</td>
</tr>
</tbody>
</table>

Figure 3.35: Momentum (a)(b) and angular (c)(d) distributions of the inclusive $K^0$ measurement in the photon energy regions (a)(c) from 0.90 to 1.00 GeV and (b)(d) from 1.00 to 1.08 GeV. The background contributions for B.G.(1) (green squares) and B.G.(2) (blue triangles) are shown (see Sec. 3.4.1).

3.5.0.2 Event distribution of the inclusive $\Lambda$ measurement

Figure 3.37 shows the momentum and the angular distributions of the inclusive $\Lambda$ measurement after the event selections described in Table 3.2. The background contributions estimated using the side bands of the $p\pi^-$ invariant mass spectra are represented as the red squares and the green triangles in these figures. Figure 3.38 shows the momentum distributions of the inclusive $\Lambda$ measurement for each angle.

3.6 Detector Acceptance

The acceptances were estimated using the Monte-Carlo simulation based on Geant4. Then the geometries of the detector system and the target were considered realistically. The particles generated with the uniform distribution in the target along the beam line ($z$-axis). The event trigger in this simulation was required to be same as that in the experiment (see Sec. 2.6.2). The events satisfied the trigger condition were analyzed by the same program code and required the same selections as that of the experiment (see Table 3.2). Then, the resolutions which were
estimated from the experimental data was smearing to the simulated data. The resolutions and the efficiencies assumed in this simulation were summarized in Table 3.6. Here, the resolution of IH was worse than the estimated one from the $e^+e^-$ events. The hadronic events have the large angular distribution while the $e^+e^-$ events extend on the horizontal plane. The dependence of the hit position in the IH counter cannot be taken away because the signals of IH were read from the one side. The assumed resolution of IH included this effect.

The beam position and size are important factors in the estimation of the acceptance. The beam position was adjusted to about $+2$ mm in the $x$-axis by accelerator staffs in the early experimental period. However, the position shifted gradually toward the minus direction of the $x$-axis in the period. The stability of the beam position for each period is shown in Fig. 3.39. The averaged values for each period as shown in Table 3.7 were used in this simulation.
Figure 3.38: Momentum distributions of the inclusive Λ measurement in the photon energy (a) from 0.90 to 1.00 GeV and (b) from 1.00 to 1.08 GeV. The integral regions of the angular range in the laboratory system are displayed in each spectrum.

Figure 3.39: Stability of the beam position for each period of the present experiment

Table 3.6: Summary of the resolutions and the efficiencies assumed for each detector in the Monte-Carlo simulation

<table>
<thead>
<tr>
<th>Name</th>
<th>Resolution</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>IH</td>
<td>280 psec</td>
<td>1.00</td>
</tr>
<tr>
<td>OHV</td>
<td>250 psec</td>
<td>1.00</td>
</tr>
<tr>
<td>OHH</td>
<td>210 psec</td>
<td>1.00</td>
</tr>
<tr>
<td>SDC (layer1-3)</td>
<td>150 µm</td>
<td>0.97</td>
</tr>
<tr>
<td>CDC (layer4-11)</td>
<td>200 µm</td>
<td>0.97</td>
</tr>
<tr>
<td>CDC (layer12-13)</td>
<td>260 µm</td>
<td>0.97</td>
</tr>
</tbody>
</table>

3.6.1 Estimation of acceptance

3.6.1.1 acceptance of the inclusive $K^0$ measurement

In the Monte-Carlo simulation for the estimation of the acceptance, $K^0$ decay to $\pi^+\pi^-$ with the probability of 100%. The effect of the branching ratio was considered in the calculation.
Table 3.7: Beam position and size for each period

<table>
<thead>
<tr>
<th>Period</th>
<th>Beam Position [mm]</th>
<th>Beam Size [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>December</td>
<td>+2.56</td>
<td>0.42</td>
</tr>
<tr>
<td>January</td>
<td>−0.88</td>
<td>0.40</td>
</tr>
<tr>
<td>June</td>
<td>+0.67</td>
<td>0.41</td>
</tr>
</tbody>
</table>

of the cross section discussed in Sec. 3.8. $K^0$ was generated with the momentum from 0.0 to 1.0 GeV/c and the angle $(\cos\theta_{K^0}^{\text{Lab}})$ from 0.5 to 1.0 in the laboratory system. The number of the generated $K^0$ was 100 million for the geometry of each experimental period. Figure 3.40 shows the acceptance of the $K^0 \rightarrow \pi^+\pi^−$ decay mode. The acceptance is extended for generated $K^0$ with the high momentum and to the forward angle against that of NKS. This is because the detector design of NKS2 was optimized to cover the forward region.

The detectors of NKS2 had not been moved in the experimental period. Therefore, the difference of the acceptance for each period was caused by the position of the target and the beam. The difference of the acceptance for each period is very small.

![Figure 3.40: Acceptance of $K^0 \rightarrow \pi^+\pi^−$ decay mode. The lower left figure represents the contour plot by 0.5%. The right figure shows that of the momentum dependence by each angle in the laboratory system.](image)

3.6.1.2 acceptance of the inclusive $\Lambda$ measurement

In the same way as the inclusive $K^0$ measurement, $\Lambda$ decay to $p\pi^−$ with the probability of 100%. The effect of the branching ratio was considered in the calculation of the cross section as $\Lambda$. $\Lambda$ was generated with the momentum from 0.0 to 1.2 GeV/c and the angle $(\cos\theta_{\Lambda}^{\text{Lab}})$ from 0.75 to 1.00 in the laboratory system. The number of the generated $\Lambda$ was 100 million for the geometry of each experimental period. Figure 3.41 shows the acceptance of the $\Lambda \rightarrow p\pi^−$ decay...
mode. The acceptance for the inclusive Λ measurement has increased greatly by covering the forward region and no use of EV in the downstream of the target. Although the experimental data cannot be directly compared for no analyzed data of NKS, the yield of the inclusive Λ increases by a factor of ten according to the simulation.

The difference of the acceptance for each period is larger than that for the inclusive \( K^0 \) measurement. The reason is the difference of the beam position. The shift of the beam position means the relative position between the window in IH and the beam. The angular distribution of proton from Λ decay become forward in the laboratory system. Therefore, the relative position of the window in IH strongly influences the acceptance.

![Graphs showing acceptance and momentum distribution](image)

**Figure 3.41:** Acceptance of \( \Lambda \rightarrow p\pi^- \) decay mode. The lower left figure represents the contour plot by 0.5%. The right figure shows that of the momentum dependence by each angle in the laboratory system.

### 3.6.2 Systematic error estimation of acceptance

#### 3.6.2.1 Systematic error of acceptance for the inclusive \( K^0 \) measurement

The systematic error was estimated using the assessment of reproducibility and the indeterminacy of the detectors and the target positions. Although the simulated data for the reproducibility was generated under the same conditions of resolutions and efficiencies as that for the acceptance, the error of the reproducibility is larger than the statistical one. It causes for the the finite binning and the finite detector resolutions. The binning of the acceptance map was optimized as the smaller reproducibility error. The widths of a bin were 0.025 GeV/c for the momentum and 0.01 for the angle (\( \cos \theta_{\Lambda}^{\text{Lab}} \)). However, the systematic error becomes still about 4%. Moreover, the ambiguities between the target positions and the decay volume selection were estimated to be under ±0.5 mm. The ambiguities of the beam condition can be confirmed in Fig. 3.39 and then the systematical ambiguities of the acceptance from these is estimated to be about 3%. The systematic error of the acceptance from the ambiguities of the space between each IH counter is estimated geometrically to be 2% by a charged particle. The
3.7. NORMALIZATION

Systematical ambiguities of the acceptance were estimated using the error propagation of these components to be 8%.

3.6.2.2 Systematic error of acceptance for the inclusive $\Lambda$ measurement

In the same way as the inclusive $K^0$ measurement, the widths of a bin were optimized to be 0.025 GeV/c for the momentum and 0.005 for the angle ($\cos \theta_{\Lambda}^{\text{Lab}}$). The systematical ambiguities of the acceptance were estimated using the error propagation of these components to be 13%. This systematical error for the inclusive $\Lambda$ measurement is larger than that for the inclusive $K^0$ measurement. Because the systematical error for the acceptance from the ambiguities of the beam condition becomes larger by decay proton from $\Lambda$ to have the forward distribution in the laboratory system (about 10%). The vertical position of the vertex point is not relatively precise. Therefore, the ambiguities of the beam position and the beam size have to become larger. If IHL1 and IHR1, which was installed to the tops and bottoms in the downstream of the beam, is used, this ambiguities have a great influence on the systematical error. Therefore, IHL1 and IHR1 was not used for the present analysis of inclusive $\Lambda$ measurement.

3.7 Normalization

3.7.1 Effective number of photons

The effective number of photons bombarding on the target was estimated from the scaler value of TagF which measured the number of scattered electrons. However, the scaler value could not be directly taken as the number of photons by the following reasons:

- After a photon is generated, a scattered electron hits two neighbor TagFs;
- Although two and more photons generate simultaneously, these events are not used to be able to distinguish the reacted photon;
- Although a photon is not generated, there is a hit on TagF for the accidental coincidence between TagF and TagB;
- The number of generated photons decreased at the target position, because the some photons converted to $e^+e^-$ pairs by passing through the materials of the target upstream.

The rejection efficiency of the first three items is defined as the tagger analysis efficiency ($\epsilon_{\text{tagana}}$). That of the last item is named tagging efficiency ($\epsilon_{\text{tagging}}$).

The effective number of photons by a integer segment ($i$) are calculated as follows,

$$N_{\gamma}^i = N_{\text{scaler}}^i \cdot \epsilon_{\text{CS1, tagana}}^i \cdot \epsilon_{\text{tagging}}^i,$$

and that by a half-integer segment ($i + 1/2$) are as follows,

$$N_{\gamma}^{i+1/2} = N_{\text{scaler}}^i \cdot \epsilon_{\text{CS2, tagana}, More, i} \cdot \epsilon_{\text{tagging}}^i + N_{\text{scaler}}^{i+1} \cdot \epsilon_{\text{CS2, Less, tagana}, i+1} \cdot \epsilon_{\text{tagging}}^{i+1},$$

where $N_{\gamma}^i$, $N_{\text{scaler}}^i$ and $\epsilon_{\text{tagging}}^i$ are the effective number of photons, the number of scalers and the tagging efficiency by a segment $i$, respectively. The $\epsilon_{\text{CS1, tagana}}$, $\epsilon_{\text{CS2, More, tagana}}$, and $\epsilon_{\text{CS2, Less, tagana}}$ are a kind of the tagger analysis efficiencies. These efficiencies are explained in the following in detail.
3.7.1.1 Tagger analysis efficiency

The tagger analysis efficiency means the ratio between the scaler value of TagF and the effective number of the generated photons in the analysis. It is mainly influenced by the events which one scattered electron hits two TagF counters. Additionally, it includes the rejected events for the accidental coincidence and the events generated simultaneously. These amount strongly depend on the counting rate of the tagger. Therefore, this efficiency was estimated for each rate by the spill. The information of TDC by the tagger runs, which is not influenced by the trigger of the spectrometer side, was used for the estimation. The cut condition of tagger is mentioned in Sec. 3.2.3.

The tagger analysis efficiency by a integer segment \((i)\) was defined as follows,

\[
\epsilon_{\text{tagana}}^{\text{CS}1, i} = \frac{N_{\text{TagSH}}^{\text{CS}1, i}}{N_{\text{TagF}}^i},
\]

where \(N_{\text{TagF}}^i\) and \(N_{\text{TagSH}}^{\text{CS}1, i}\) are the number of TagF hits and the number of TagSH hits with cluster size 1, respectively. Moreover, the tagger analysis efficiency with cluster size 2 was defined as follows,

\[
\epsilon_{\text{tagana}}^{\text{CS}2wMore, i} = \frac{1}{2} \frac{N_{\text{TagSH}}^{\text{CS}2wMore, i}}{N_{\text{TagF}}^i},
\]

\[
\epsilon_{\text{tagana}}^{\text{CS}2wLess, i} = \frac{1}{2} \frac{N_{\text{TagSH}}^{\text{CS}2wLess, i}}{N_{\text{TagF}}^i},
\]

where \(N_{\text{TagSH}}^{\text{CS}2wMore, i}\) and \(N_{\text{TagSH}}^{\text{CS}2wLess, i}\) are the number of TagSH hits making the cluster with one more segment and with one less, respectively. In the extensive interpretation, the following efficiencies are used,

\[
\epsilon_{\text{tagana}}^{\text{CS}1, \text{CS}2, i} = \epsilon_{\text{tagana}}^{\text{CS}1, i} + \epsilon_{\text{tagana}}^{\text{CS}2wMore, i} + \epsilon_{\text{tagana}}^{\text{CS}2wLess, i},
\]

\[
\epsilon_{\text{tagana}}^{\text{CS}2, i} = \epsilon_{\text{tagana}}^{\text{CS}2wMore, i} + \epsilon_{\text{tagana}}^{\text{CS}2wLess, i},
\]

these efficiencies are used only for the interpretation and are not used for the calculation of the effective number of photons.

Figure 3.42(a) shows the hit pattern of TagSH at the rate of the summed TagF hits from 1.7 MHz to 1.8 MHz. The black line shows that of TagF without the cut. The red and green histograms represent that of TagSH with the cluster size of 1 and 2, respectively. Figure 3.42(b) shows the tagger analysis efficiency for the dependence of the tagger segment. Moreover, this efficiency for the rate dependence of the summed TagF hits is represented in Fig. 3.42(c). The effective number of the generated photons in the analysis was corrected by spill using the scaler value due to the rate dependence. Table 3.8 shows the tagger analysis efficiency for each period. The difference of the efficiency for each period was small.

Figure 3.43(a) shows the detail of the tagger analysis efficiency at the rate of the summed TagF hits from 1.7 MHz to 1.8 MHz. The ratio between \(\epsilon_{\text{tagana}}^{\text{CS}2, i}\) (closed red squares) and \(\epsilon_{\text{tagana}}^{\text{CS}1, i}\) (green triangles) is seen. The each component of this efficiency with two size cluster, which means the cluster made with one more \(\epsilon_{\text{tagana}}^{\text{CS}2wMore, i}\) : blue pluses) or one less segment \(\epsilon_{\text{tagana}}^{\text{CS}2wLess, i}\) yellow asterisks), is represented in Fig. 3.43(b).
Figure 3.42: Tagger hit pattern and tagger analysis efficiencies for each period. (a) Hit pattern of TagSH at the rate of the summed TagF hits from 1.7 MHz to 1.8 MHz. The black line shows that of TagF without the cut. The red and green histograms represent one of the cluster size of 1 and 2, respectively. (b) Tagger analysis efficiency for the dependence of the segment at the rate from 1.7 MHz to 1.8 MHz. (c) Tagger analysis efficiency for the rate dependence.

Table 3.8: Typical tagger analysis efficiency for each period

<table>
<thead>
<tr>
<th>Period</th>
<th>Typical $\epsilon_{\text{tagana}}$ [%]</th>
<th>Average of $\epsilon_{\text{tagana}}$ [%]</th>
<th>Syst. Error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>December</td>
<td>83.1 ± 0.2(stat.)</td>
<td>79.7 ± 0.2(stat.)</td>
<td></td>
</tr>
<tr>
<td>January</td>
<td>82.2 ± 0.1(stat.)</td>
<td>79.3 ± 0.1(stat.)</td>
<td>± 1.2</td>
</tr>
<tr>
<td>June</td>
<td>82.8 ± 0.1(stat.)</td>
<td>79.3 ± 0.1(stat.)</td>
<td></td>
</tr>
<tr>
<td>average</td>
<td>82.7 ± 0.1(stat.)</td>
<td>79.4 ± 0.1(stat.)</td>
<td>± 1.2</td>
</tr>
</tbody>
</table>

3.7.1.2 Tagging efficiency

The tagging efficiency means how many photons recognized in the analysis bomb on the target. The measurement of the tagging efficiency was performed with the lead glass Čerenkov
counter (LG) located at the 3.6 m downstream from the target. The beam intensity of the tagging efficiency runs was faint due to the limitation of the counting rate of LG. It does not fundamentally depend on the beam rate, if the direction of the beam does not change. Because the tagging efficiency depends only on the materials between the radiator and the deuteron target.

The tagging efficiency was defined by

$$\epsilon_{\text{tagging}}^i = \frac{1}{f_{\text{att.}}} \cdot \frac{N_{(\text{TagSH} \cap \text{LG})}}{N_{\text{TagSH}^i}},$$

(3.49)

where $N_{\text{TagSH}^i}$ and $N_{(\text{TagSH} \cap \text{LG})}$ is the number of TagSH of the segment(i) and that with the LG hits, respectively. The $f_{\text{att.}}$ is the attenuation factor by the photon conversion for the materials between the target and LG.

Figure 3.44 shows the tagging efficiency in each period. When measuring the tagging efficiency run two or more times in a month, the efficiency was estimated by the adding data by the month. The $f_{\text{att.}}$ depends only on the radiation length of the materials between the target and LG at least in principle. However, it remains the probability that LG detected the $e^+$ or $e^-$ converted from $\gamma$ before LG because of no charged veto counter. Therefore, the $f_{\text{att.}}$ was estimated by the Monte-Carlo simulation considering this probability. The estimated factor was 0.995. Table 3.9 shows the tagger analysis efficiency for each period. The systematic error was estimated to be 0.9 % from the monthly difference and the uncertainly of the $f_{\text{att.}}$. 

Figure 3.43: Detail of the tagger analysis efficiencies. (a) Detail of the tagger analysis efficiency at the rate of the summed TagF hits from 1.7 MHz to 1.8 MHz. The red squares and the green triangles represent that of the cluster size of 1 and 2, respectively. (b) Each component of this efficiency with two size cluster. The blue pluses and the yellow asterisks show that of the cluster made with one more and one less segment, respectively.
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Table 3.9: Typical tagging efficiency for each period

<table>
<thead>
<tr>
<th>Period</th>
<th>Typical $\epsilon_{tagging}$ [%]</th>
<th>Average of $\epsilon_{tagging}$ [%]</th>
<th>Syst. Error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>December</td>
<td>81.1 ± 0.4(stat.)</td>
<td>80.2 ± 0.4(stat.)</td>
<td>± 0.9</td>
</tr>
<tr>
<td>January</td>
<td>81.4 ± 0.5(stat.)</td>
<td>80.0 ± 0.5(stat.)</td>
<td>± 0.9</td>
</tr>
<tr>
<td>June</td>
<td>81.4 ± 0.2(stat.)</td>
<td>80.1 ± 0.2(stat.)</td>
<td>± 0.9</td>
</tr>
<tr>
<td>average</td>
<td>81.3 ± 0.2(stat.)</td>
<td>80.1 ± 0.4(stat.)</td>
<td>± 0.9</td>
</tr>
</tbody>
</table>

3.7.1.3 Total effective number of photons

The effective number of photons is represented as Eq. (3.42). The total effective number of photons was defined as the summation of that within an energy region. The photon energy is discussed in Sec. 3.2.3. The total effective number of photons is summarized in Table 3.10.

Table 3.10: Summary of the total effective number of photons for each photon energy region.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.80 $&lt; E_\gamma \leq$ 0.90</td>
<td>29 $\leq i \leq$ 44.5</td>
<td>7.76 $\times 10^{11}$</td>
<td>1.23 $\times 10^{8}$</td>
<td></td>
</tr>
<tr>
<td>0.90 $&lt; E_\gamma \leq$ 1.00</td>
<td>13.0 $\leq i \leq$ 28.5</td>
<td>7.26 $\times 10^{11}$</td>
<td>1.43 $\times 10^{8}$</td>
<td></td>
</tr>
<tr>
<td>1.00 $&lt; E_\gamma \leq$ 1.08</td>
<td>1 $\leq i \leq$ 12.5</td>
<td>5.30 $\times 10^{11}$</td>
<td>1.48 $\times 10^{8}$</td>
<td></td>
</tr>
<tr>
<td>0.80 $&lt; E_\gamma \leq$ 0.85</td>
<td>37 $\leq i \leq$ 44.5</td>
<td>3.94 $\times 10^{11}$</td>
<td>7.12 $\times 10^{7}$</td>
<td></td>
</tr>
<tr>
<td>0.85 $&lt; E_\gamma \leq$ 0.90</td>
<td>29 $\leq i \leq$ 36.5</td>
<td>3.82 $\times 10^{11}$</td>
<td>1.00 $\times 10^{8}$</td>
<td>2.1</td>
</tr>
<tr>
<td>0.90 $&lt; E_\gamma \leq$ 0.95</td>
<td>21.0 $\leq i \leq$ 28.5</td>
<td>3.71 $\times 10^{11}$</td>
<td>1.01 $\times 10^{8}$</td>
<td></td>
</tr>
<tr>
<td>0.95 $&lt; E_\gamma \leq$ 1.00</td>
<td>13.0 $\leq i \leq$ 20.5</td>
<td>3.56 $\times 10^{11}$</td>
<td>1.00 $\times 10^{8}$</td>
<td>2.1</td>
</tr>
<tr>
<td>1.00 $&lt; E_\gamma \leq$ 1.05</td>
<td>5 $\leq i \leq$ 12.5</td>
<td>3.52 $\times 10^{11}$</td>
<td>1.00 $\times 10^{8}$</td>
<td></td>
</tr>
<tr>
<td>1.05 $&lt; E_\gamma \leq$ 1.08</td>
<td>1 $\leq i \leq$ 4.5</td>
<td>1.78 $\times 10^{11}$</td>
<td>1.08 $\times 10^{8}$</td>
<td></td>
</tr>
</tbody>
</table>
3.7.2 Number of deuterons in the target

In these experimental periods, the pressure and the temperature of the liquid deuterium were monitored and recorded as mathematical values. The density of the liquid deuterium was calculated from these data. Figure 3.45 shows the status of the liquid deuterium through the experimental period in December 2006 as the reference. The pressure (a) decreased slowly with time and the variation width of that diminished progressively. However this decrease has a relatively small effect on the density. In the experimental period of January 2007, the temperature of the liquid deuterium was increased sharply for the trouble of the network system as shown in Fig. 3.46. This increase influences the density of the liquid deuterium measurably. Therefore, the number of deuterons in the target was calculated in the first and last half in this period.

![Figure 3.45](image1)

Figure 3.45: Typical status of the liquid deuterium. The status of the experimental period in December 2006 is shown as a reference. The influence of the decreasing pressure (a) is small to the calculated density (c).

![Figure 3.46](image2)

Figure 3.46: Temperature of the liquid deuterium in January 2007. The temperature was increased sharply for the trouble of the network system.
3.7. NORMALIZATION

The thickness of the target cell is 29.7 mm introduced in Sec. 2.5.3. However, it is obvious that the thickness of the target from the vertex distribution indicated larger than that of the target cell. It is cause that the films of the target cell expanded by the pressure in the target cell. Therefore, the effective thickness of the target, which means the average of thickness through the photon beam, has to estimated. It was calculated using the Monte-Carlo simulation. The expansion of the target was measured at room temperature and estimated to be about 1.65 mm at the center of the target cell. And these shape obtained from the measurement was as closer as to the sphere than the modeling. The beam went through about 8.2 mm lower point from the target center and the beam size was gotten from the analysis. Figure 3.47 shows the result of the simulation using these parameters. The effective thickness of the target is estimated to be 31.9 mm. The uncertainties in the assumption of the sphere was estimated to be about 0.2 mm and the amount of expansion for the pressure in each period was estimated to be 0.2 mm. The systematic error was to be 1.0 mm besides that from the initial parameters.

The effective thickness estimated using the Monte-Carlo simulation consists with that using the vertex distribution.

![Diagram](attachment:image.png)

Figure 3.47: Effective thickness of the deuteron target. (a) Schematic view of the target cell. The definitions of the beam offset and target expansion are shown. (b) Correlation between the effective thickness and the condition of the beam. (c) Dependence of the thickness on the expansion of the films.
The effective number of deuterons in the target is estimated to be $0.166 \pm 0.05 (\text{syst.}) \, \mu b$. In this calculation, the mass number of deuteron is $2.01410177803 \, \text{u}$ and Avogadro constant is $6.02214179 \times 10^{23}$ from PDG.

The target condition and the effective number of deuterons are summarized in Table 3.11.

<table>
<thead>
<tr>
<th>Period</th>
<th>Pressure [kPa]</th>
<th>Temperature [K]</th>
<th>Density [g/cm$^3$]</th>
<th>Thickness [cm]</th>
<th>#Deuteron [µb$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>December</td>
<td>46.4</td>
<td>18.8</td>
<td>$0.174 \pm 0.001$</td>
<td>0.166</td>
<td>$0.166 \pm 0.005$</td>
</tr>
<tr>
<td>January(first)</td>
<td>51.3</td>
<td>18.8</td>
<td>$0.174 \pm 0.001$</td>
<td>3.19</td>
<td>$0.165 \pm 0.005$</td>
</tr>
<tr>
<td>January(last)</td>
<td>49.7</td>
<td>19.6</td>
<td>$0.172 \pm 0.001$</td>
<td>$3.19 \pm 0.10$</td>
<td>$0.164 \pm 0.005$</td>
</tr>
<tr>
<td>June</td>
<td>51.6</td>
<td>18.8</td>
<td>$0.174 \pm 0.001$</td>
<td>0.164</td>
<td>$0.166 \pm 0.005$</td>
</tr>
<tr>
<td>average</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$0.166 \pm 0.005$</td>
</tr>
</tbody>
</table>

### 3.7.3 Efficiency of the data acquisition

The efficiency of the data acquisition (efficiency of DAQ: $\epsilon_{DAQ}$) is defined as the follows,

$$\epsilon_{DAQ} = \frac{\sum N_{\text{accepted}}}{\sum N_{\text{requested}}}, \quad (3.50)$$

where $N_{\text{accepted}}$ and $N_{\text{requested}}$ represents the number of accepted triggers and requested triggers, respectively. The both numbers were recorded by CAMAC scaler in every runs. Table 3.12 shows the efficiency of DAQ for each period. The efficiency of the period in January 2007 is lower than that of other periods because the beam rate was higher. In this analysis, the efficiency of DAQ was estimated to be 0.728.

Table 3.12: Efficiency of the data acquisition for each period.

<table>
<thead>
<tr>
<th>Period</th>
<th>$\epsilon_{DAQ}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>December</td>
<td>$73.3 &lt; 0.1(\text{syst.})$</td>
</tr>
<tr>
<td>January</td>
<td>$68.3 &lt; 0.1(\text{syst.})$</td>
</tr>
<tr>
<td>June</td>
<td>$74.5 &lt; 0.1(\text{syst.})$</td>
</tr>
<tr>
<td>average</td>
<td>$72.8 &lt; 0.1(\text{syst.})$</td>
</tr>
</tbody>
</table>

### 3.7.4 Tracking Efficiency

The tracking efficiencies are separated as follows,

- efficiency of multiplicity of layer hits,
- efficiency of the number of hits in the track,
3.7. NORMALIZATION

- efficiency of the $\chi^2$ selection,
- efficiency of the residual distance to hodoscope.

The efficiency of the multiplicity of layer hits means the survival ratio after the MLH selection as discussed in Sec. 3.2.2.1. It was applied for the analysis of only the experimental data. On the other hand, the other efficiencies were estimated for the analyses of not only the experimental data but also the simulated data. The ratios of these efficiencies were applied as the normalization factors.

3.7.4.1 Efficiency of the multiplicity of layer hits

The event with the large maximum multiplicity of layer hits (MLH) was rejected because it needs huge analysis time as mentioned in Sec. 3.2.2. Only the events with MLH under twenty were analyzed in the present analysis.

The efficiency for MLH selection ($\epsilon_{\text{MLH}}$) was estimated using the following method. The condition of MLH selection was allowed up to 40, a few hundredth of events were sampled and analyzed. Figure 3.48 shows the correlation between MLH and the yield for $\pi^+\pi^-$ and $p\pi^-$ events. Here, the number of events is normalized so that it becomes 1 at 20 of MLH. Also, the correlation between MLH and the increased yield by changed one MLH were fitted using the exponential function. The efficiency of MLH selection was estimated for integrating this function from 21 to infinity. Table 3.13 shows the efficiency of MLH selection for each period. In this analysis, the efficiency of MLH selection was estimated to be $0.969 \pm 0.001$. The systematic error was estimated to be 0.007.

<table>
<thead>
<tr>
<th>Period</th>
<th>$\epsilon_{\text{MLH}}$ of $\pi^+\pi^-$ [%]</th>
<th>$\epsilon_{\text{MLH}}$ of $p\pi^-$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>December</td>
<td>$97.7 \pm 0.1$ (stat.)</td>
<td>$97.5 \pm 0.1$ (stat.)</td>
</tr>
<tr>
<td>January</td>
<td>$96.0 \pm 0.1$ (stat.)</td>
<td>$96.1 \pm 0.1$ (stat.)</td>
</tr>
<tr>
<td>June</td>
<td>$97.0 \pm 0.1$ (stat.)</td>
<td>$96.8 \pm 0.1$ (stat.)</td>
</tr>
<tr>
<td>average</td>
<td>$96.9 \pm 0.1$ (stat.) $\pm 0.7$ (syst.)</td>
<td></td>
</tr>
</tbody>
</table>

3.7.4.2 Efficiency of the number of hits in the track

As mentioned in Sec. 3.3.1, the number of hits in the track with more than 6 hits at least is required. The efficiency of this selection represents, when the $\chi^2$ selection and the closest distance selection was not used. The denominator means the number of charged particles. The efficiency was estimated using the correlation between the number of hits in the track and the yield, when the condition of the tracking requirement was dropped. The efficiency of the number of hits in the track was summarized in Table 3.14. The normalization factor ($\epsilon_{\text{nhits}}$) for the $K^0$ measurement was estimated to be $0.981 \pm 0.032$ (syst.) and that for the $\Lambda$ measurement was to be $0.994 \pm 0.022$ (syst.).
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Figure 3.48: Correlation between the number of events and MLH selection. The number of events is normalized so that it becomes 1 at 20 of MLH

Table 3.14: Efficiency of the number of hits in the track for two particles

<table>
<thead>
<tr>
<th>Data</th>
<th>efficiency/normalization factor for the $K^0$ measurement</th>
<th>efficiency/normalization factor for the $\Lambda$ measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>experimental data</td>
<td>96.6 ± 3.5(syst.) [%]</td>
<td>96.6 ± 2.2(syst.) [%]</td>
</tr>
<tr>
<td>simulated data</td>
<td>98.5 ± 0.4(syst.) [%]</td>
<td>97.2 ± 0.2(syst.) [%]</td>
</tr>
<tr>
<td>normalization factor</td>
<td>0.981 ± 0.032(syst.)</td>
<td>0.994 ± 0.022(syst.)</td>
</tr>
</tbody>
</table>

3.7.4.3 Efficiency of the $\chi^2$ selection

The efficiency of the $\chi^2$ selection was estimated using the events requiring the selection of the number of hit layers in the track. Here, the closest distance selection was not used. The efficiency was estimated using the correlation between the cutoff point for the chi-square and the yield. Figure 3.49 shows the correlation for $K^0$ and $\Lambda$ events. The efficiency for the $\Lambda$ measurement (right) is clearly smaller than that for the $K^0$ (left). The yield of $K^0$ and $\Lambda$ events is normalized so that it becomes 1 at the yields of $\chi^2 < 8$, respectively. It causes the chi-square for $\pi^-$ from the $\Lambda$ decay was wrong. This tendency was reproduced by the Monte-Carlo simulation
and was attributed to the multiple scattering. The efficiency of the $\chi^2$ selection was summarized in Table 3.15. The normalization factor ($\epsilon_{\chi^2}$) for the $K^0$ measurement was estimated to be $0.985 \pm 0.024$ (syst.) and that for the $\Lambda$ measurement was to be $0.972 \pm 0.027$ (syst.).

**Table 3.15: Efficiency of the $\chi^2$ selection for two particles**

<table>
<thead>
<tr>
<th>Data</th>
<th>efficiency/normalization factor for the $K^0$ measurement</th>
<th>efficiency/normalization factor for the $\Lambda$ measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>experimental data</td>
<td>$94.7 \pm 2.3$ (syst.) [%]</td>
<td>$91.2 \pm 2.6$ (syst.) [%]</td>
</tr>
<tr>
<td>simulated data</td>
<td>$96.2 \pm 0.5$ (syst.) [%]</td>
<td>$93.8 \pm 0.7$ (syst.) [%]</td>
</tr>
<tr>
<td>normalization factor</td>
<td>$0.985 \pm 0.024$ (syst.)</td>
<td>$0.972 \pm 0.027$ (syst.)</td>
</tr>
</tbody>
</table>

3.7.4.4 Efficiency of the residual distance to hodoscope

As mentioned in Sec. 3.3.1, the residual distance between the center of the hit hodoscope and the trajectory, which is hereafter called the hodoscope distance, is expressed as the distance in the horizontal plane. The efficiency of the hodoscope distance for IH and OHV, who plastic scintillators were located vertically, was considered to be the negligible-small. The efficiency was estimated using the correlation between the cutoff point for the hodoscope distance and the yield. Here, the selection number of hit layers in the track and the $\chi^2$ selection were already required. The efficiency of the hodoscope distance was summarized in Table 3.16. In the present analysis, the normalization factor ($\epsilon_{\text{hodo}}$) for the $K^0$ measurement was estimated to be $0.971 \pm 0.022$ (syst.) and that for the $\Lambda$ measurement was to be $0.995 \pm 0.013$ (syst.).

3.7.5 Ratio of the lost events in the trigger level

There are some processes to lose the events in the trigger level. Some in those processes, which have the great influence for the cross section, are as follows:

- An actual event was rejected by a veto accidentally by EV.
Table 3.16: Efficiency of the hodoscope distance for two particles

<table>
<thead>
<tr>
<th>Data</th>
<th>Efficiency/normalization factor for the $K^0$ measurement</th>
<th>Efficiency/normalization factor for the $\Lambda$ measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>experimental data</td>
<td>98.9 ± 2.1(syst.) [%]</td>
<td>99.1 ± 1.2(syst.) [%]</td>
</tr>
<tr>
<td>simulated data</td>
<td>99.7 ± 0.2(syst.) [%]</td>
<td>99.6 ± 0.3(syst.) [%]</td>
</tr>
<tr>
<td>normalization factor</td>
<td>0.971 ± 0.022(syst.)</td>
<td>0.995 ± 0.013(syst.)</td>
</tr>
</tbody>
</table>

- An actual event was masked in the logic to make the trigger.
- An actual event was rejected by a veto to hit EV by the decay particle of hyperon which is generated simultaneously with $K^0$.

The efficiencies for these processes is discussed after this.

### 3.7.5.1 Accidental kill by EV

In this experiment, the veto signals by EV4 were used due to the rejection of the background events in the trigger. Under the high rate condition, some events not to related to hit the EV4 counter were rejected by a veto signal in the trigger for the accidental coincidence. The survival ratio of the accidental kill by EV ($\epsilon_{EV}$) was estimated using the scaler value of the veto signals and the width by spill. The survival ratio of the accidental kill for each period was summarized in Table 3.17.

Table 3.17: Survival ratio of the accidental kill by EV

<table>
<thead>
<tr>
<th>Period</th>
<th>Survival ratio ($\epsilon_{EV}$) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>December</td>
<td>99.6 &lt; 0.1(stat.) &lt; 0.1(syst.)</td>
</tr>
<tr>
<td>January</td>
<td>99.4 &lt; 0.1(stat.) ± 0.2(syst.)</td>
</tr>
<tr>
<td>June(first half)</td>
<td>99.5 &lt; 0.1(stat.) &lt; 0.1(syst.)</td>
</tr>
<tr>
<td>June(last half)</td>
<td>98.8 &lt; 0.1(stat.) ± 0.3(syst.)</td>
</tr>
<tr>
<td>average</td>
<td>99.4 &lt; 0.1(stat.) ± 0.2(syst.)</td>
</tr>
</tbody>
</table>

### 3.7.5.2 Event mask in the logic

The coincidence width between the signal of IH and the signal of the tagger is so narrow as possible due to the suppression of the accidental coincidence. The signals of tagger for the trigger were sent with the width of 40 nsec from the experimental hall introduced in Sec. 2.6.1. These signals were reformed to the width of 8 nsec after going through the logical addition by the FANIN/FANOUT module. There is the mechanism of the masked signal of tagger in this process. Figure 3.50 shows the mechanism of the event mask.

The survival ratio of the event mask ($\epsilon_{mask}$) was estimated using the scaler value of $\Sigma$Tag and masked region by the spill. The measured value of $\Sigma$Tag is already masked in order to use the same logic. Figure 3.51 shows the ratio between masked events and actual events. The masked region become 46 nsec by a signal for the consider of the coincidence width. This region
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Figure 3.50: Mechanism of event mask in the trigger. The upper figure shows the logic of the coincidence between tagger and IH in the trigger. The figure of lower right shows the time chart of an example. A signal of ΣTag02 is masked at the output signal of the LED. The figure of lower left shows the dead region. It becomes 46 nsec by a signal of the tagger for the consider of the coincidence width.

was considered as plus or minus 8 nsec with the systematic error. The survival ratio of the event mask in the trigger logic for each period is summarized in Table 3.11.

![Diagram](image)

3.7.5.3 Inevitable kill by the undetected particle

In kaon photoproductions, not only kaon but also hyperon was generated due to the conservation of strangeness. In the present experiment, all particles of final state were not necessarily
detected. Some generated particle or decayed particle hit EV4. Focus to $K^0$ particle, some $p\pi^-$ decayed by $\Lambda$ particle, which generated with $K^0$ simultaneously, made the veto signal to hit EV4 in the trigger. The acceptance made for generated one particle does not include this effect.

The survival ratio of this inevitable kill ($\epsilon_{\text{inve}}$) was estimated using the Monte Carlo simulation. The efficiency for the inclusive $K^0$ measurement was estimated to be $0.997 \pm 0.003$ (syst.) assuming the $\gamma n \rightarrow K^0\Lambda$ process. The efficiency for the inclusive $\Lambda$ measurement was estimated to be $0.995 \pm 0.003$ (syst.) and $0.998 \pm 0.002$ (syst.) assuming the $\gamma n \rightarrow K^0\Lambda$ process and the $\gamma p \rightarrow K^+\Lambda$ process, respectively. In the present analysis, the averaged value was used for the efficiency of the inclusive $\Lambda$ measurement ($0.996 \pm 0.004$ (syst.)).

### 3.7.6 Efficiency of the invariant mass selection

As described in Sec. 3.3.7, the efficiency of the invariant mass selection (efficiency of IM selection: $\epsilon_{IM}$) for the inclusive $K^0$ measurement was estimated to be 98.0% and the systematic error was to be $\pm 1.8\%$. Furthermore, the efficiency of IM selection for the inclusive $\Lambda$ measurement was estimated to be 97.8% and the systematic error was to be $\pm 1.3\%$.

### 3.7.7 Efficiency of the closest distance selection

As described in Sec.3.3.3, the closest distance of two tracks within 5 cm is required as a good combination. The efficiency was estimated using the correlation between the closest distance selection and the yield. Here, the selection number of hit layers in the track, the $\chi^2$ selection and the hodoscope distance selection were already required. The efficiency of the hodoscope distance was summarized in Table 3.19. In the present analysis, the normalization factor ($\epsilon_{\text{cdist}}$) for the $K^0$ measurement was estimated to be $0.957 \pm 0.023$ (syst.) and that for the $\Lambda$ measurement was to be $0.953 \pm 0.018$ (syst.).

### Table 3.18: Survival ratio of the event mask in the trigger logic.

<table>
<thead>
<tr>
<th>Period</th>
<th>Survival ratio ($\epsilon_{\text{mask}}$) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>December</td>
<td>$92.4 &lt; 0.1$ (stat.) $\pm 1.4$ (syst.)</td>
</tr>
<tr>
<td>January</td>
<td>$90.6 &lt; 0.1$ (stat.) $\pm 1.8$ (syst.)</td>
</tr>
<tr>
<td>June</td>
<td>$91.7 &lt; 0.1$ (stat.) $\pm 1.6$ (syst.)</td>
</tr>
<tr>
<td>average</td>
<td>$91.4 &lt; 0.1$ (stat.) $\pm 1.6$ (syst.)</td>
</tr>
</tbody>
</table>

### Table 3.19: Efficiency of the closest distance selection

<table>
<thead>
<tr>
<th>Data</th>
<th>efficiency/normalization factor for the $K^0$ measurement</th>
<th>for the $\Lambda$ measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>experimental data</td>
<td>$94.4 \pm 2.2$ (syst.) [%]</td>
<td>$93.9 \pm 1.7$ (syst.) [%]</td>
</tr>
<tr>
<td>simulated data</td>
<td>$98.7 \pm 0.3$ (syst.) [%]</td>
<td>$98.5 \pm 0.3$ (syst.) [%]</td>
</tr>
<tr>
<td>normalization factor</td>
<td>$0.957 \pm 0.023$ (syst.)</td>
<td>$0.953 \pm 0.018$ (syst.)</td>
</tr>
</tbody>
</table>
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### 3.7.8 Summary of various efficiencies

The various efficiencies and the normalization factors are summarized in Table 3.20. In the inclusive $\Lambda$ measurement, not only these values but also the feedback factor in Table 3.4 were used.

<table>
<thead>
<tr>
<th>common factor (for inclusive $K^0$, inclusive $\Lambda$ and exclusive $K^0\Lambda$)</th>
<th>items</th>
<th>values</th>
<th>statistical error</th>
<th>systematical error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_\gamma$</td>
<td>number of TagF by scaler values</td>
<td>$3.25 \times 10^{12}$</td>
<td>$1.80 \times 10^6$</td>
<td>-</td>
</tr>
<tr>
<td>$\epsilon_{\text{tagana}}$</td>
<td>tagger analysis efficiency</td>
<td>0.794</td>
<td>± 0.001</td>
<td>± 0.012</td>
</tr>
<tr>
<td>$\epsilon_{\text{tagging}}$</td>
<td>tagging efficiency</td>
<td>0.798</td>
<td>± 0.004</td>
<td>± 0.009</td>
</tr>
<tr>
<td>$N_{\text{target}}$</td>
<td>number of target $[b^{-1}]$</td>
<td>0.166</td>
<td>&lt; 0.001</td>
<td>± 0.005</td>
</tr>
<tr>
<td>$\epsilon_{\text{DAQ}}$</td>
<td>efficiency of DAQ</td>
<td>0.728</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\epsilon_{\text{MLH}}$</td>
<td>efficiency of MLH selection</td>
<td>0.970</td>
<td>&lt; 0.001</td>
<td>± 0.007</td>
</tr>
<tr>
<td>$\epsilon_{\text{EV}}$</td>
<td>survival ratio of accidental kill</td>
<td>0.995</td>
<td>&lt; 0.001</td>
<td>± 0.002</td>
</tr>
<tr>
<td>$\epsilon_{\text{mask}}$</td>
<td>survival ratio of event mask</td>
<td>0.916</td>
<td>&lt; 0.001</td>
<td>± 0.016</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>factor for inclusive $K^0$</th>
<th>items</th>
<th>values</th>
<th>statistical error</th>
<th>systematical error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta$</td>
<td>branching ratio to $\pi^+\pi^-$ by $K^0_S$ and ratio of $K^0_S$ and $K^0_L$</td>
<td>$0.692 \cdot \frac{1}{2}$</td>
<td>-</td>
<td>± 0.0005 $\cdot \frac{1}{2}$</td>
</tr>
<tr>
<td>$\epsilon_{\text{IM}}$</td>
<td>efficiency of IM selection</td>
<td>0.980</td>
<td>&lt; 0.001</td>
<td>± 0.018</td>
</tr>
<tr>
<td>$\epsilon_{\text{hit}}$</td>
<td>factor for number of hit layers</td>
<td>0.981</td>
<td>&lt; 0.001</td>
<td>± 0.022</td>
</tr>
<tr>
<td>$\epsilon_{\chi^2}$</td>
<td>factor for $\chi^2$ selection</td>
<td>0.985</td>
<td>&lt; 0.001</td>
<td>± 0.027</td>
</tr>
<tr>
<td>$\epsilon_{\text{hodo}}$</td>
<td>factor for hodoscope distance</td>
<td>0.971</td>
<td>&lt; 0.001</td>
<td>± 0.022</td>
</tr>
<tr>
<td>$\epsilon_{\text{inevi}}$</td>
<td>survival ratio of inevitable mask</td>
<td>0.997</td>
<td>&lt; 0.001</td>
<td>± 0.003</td>
</tr>
<tr>
<td>$\epsilon_{\text{cdist}}$</td>
<td>factor for the closest distance cut</td>
<td>0.957</td>
<td>&lt; 0.001</td>
<td>± 0.023</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>factor for inclusive $\Lambda$</th>
<th>items</th>
<th>values</th>
<th>statistical error</th>
<th>systematical error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\eta$</td>
<td>branching ratio to $p\pi^-$ by $\Lambda$</td>
<td>0.639</td>
<td>-</td>
<td>± 0.005</td>
</tr>
<tr>
<td>$\epsilon_{\text{IM}}$</td>
<td>efficiency of IM selection</td>
<td>0.978</td>
<td>&lt; 0.001</td>
<td>± 0.013</td>
</tr>
<tr>
<td>$\epsilon_{\text{hit}}$</td>
<td>factor for number of hit layers</td>
<td>0.994</td>
<td>&lt; 0.001</td>
<td>± 0.022</td>
</tr>
<tr>
<td>$\epsilon_{\chi^2}$</td>
<td>factor for $\chi^2$ selection</td>
<td>0.972</td>
<td>&lt; 0.001</td>
<td>± 0.027</td>
</tr>
<tr>
<td>$\epsilon_{\text{hodo}}$</td>
<td>factor for hodoscope distance</td>
<td>0.995</td>
<td>&lt; 0.001</td>
<td>± 0.013</td>
</tr>
<tr>
<td>$\epsilon_{\text{inevi}}$</td>
<td>survival ratio of inevitable mask</td>
<td>0.996</td>
<td>&lt; 0.001</td>
<td>± 0.004</td>
</tr>
<tr>
<td>$\epsilon_{\text{cdist}}$</td>
<td>factor for the closest distance cut</td>
<td>0.953</td>
<td>&lt; 0.001</td>
<td>± 0.018</td>
</tr>
</tbody>
</table>
3.8 Definition of differential cross section

3.8.0.1 differential cross section of the inclusive $K^0$ measurement

The double differential cross section of the inclusive $K^0$ measurement is calculated by

$$\frac{d\sigma}{d\Omega dp} = \frac{N_{\text{yield}}^{K^0}(p, \cos \theta)}{N'_{\gamma} \cdot N_{\text{target}} \cdot \epsilon_{\text{acpt}}^{K^0}(p, \cos \theta) \cdot \eta^{K^0} \cdot \epsilon^{\text{common}} \cdot \epsilon^{K^0} \cdot 2\pi d(\cos \theta) dp}$$  \hspace{1cm} (3.51)

where $N_{\text{yield}}^{K^0}$, $N'_{\gamma}$, and $N_{\text{target}}$ are the yield of the $K^0$ events, the number of photons bombarding the target and the number of target, respectively. The number of photons bombarding the target is summarized in Table 3.10. Moreover, the number of the deuteron is discussed in Sec. 3.7.2. The $\eta^{K^0}$ denotes the acceptance for $K^0 \rightarrow \pi^+\pi^-$ decay mode for the present analysis of NKS2. The $\eta^{K^0}$ is the acceptance for $K^0 \rightarrow \pi^+\pi^-$ decay channel by $K^0_S$ and the ratio of $K^0_S$ and $K^0_L$. The $\epsilon^{\text{common}}$ and $\epsilon^{K^0}$ are various efficiencies for common and for the inclusive $K^0$ measurement.

The various efficiencies for common are given as,

$$\epsilon^{\text{common}} = \epsilon_{\text{DAQ}} \cdot \epsilon_{\text{MLH}} \cdot \epsilon_{\text{EV}} \cdot \epsilon_{\text{mask}}$$  \hspace{1cm} (3.52)

where $\epsilon_{\text{DAQ}}$ and $\epsilon_{\text{MLH}}$ are the efficiency of DAQ and that of MLH, respectively. Moreover, $\epsilon_{\text{EV}}$ and $\epsilon_{\text{mask}}$ are the survival ratio of accidental kill by EV and that of events masked, respectively. These efficiencies are summarized for the each value in Table 3.20. and are described for the estimation method in context.

The various efficiencies for the inclusive $K^0$ measurement are given as,

$$\epsilon^{K^0} = \epsilon_{1M}^{K^0} \cdot \epsilon_{\#\text{hit}}^{K^0} \cdot \epsilon_{\chi^2}^{K^0} \cdot \epsilon_{\text{hodo}}^{K^0} \cdot \epsilon_{\text{cdist}}^{K^0} \cdot \epsilon_{\text{inevi}}^{K^0}$$  \hspace{1cm} (3.53)

where $\epsilon_{1M}^{K^0}$, $\epsilon_{\#\text{hit}}^{K^0}$, $\epsilon_{\chi^2}^{K^0}$, $\epsilon_{\text{hodo}}^{K^0}$, $\epsilon_{\text{cdist}}^{K^0}$ and $\epsilon_{\text{inevi}}^{K^0}$ are the efficiency of the invariant mass selection, normalization factor for the number of layer hits, normalization factor for $\chi^2$ selection, normalization factor for the hodoscope distance selection, normalization factor for the closest distance selection and survival ratio of inevitable mask, respectively. These values are summarized in Table 3.20.

3.8.0.2 differential cross section of the inclusive $\Lambda$ measurement

The double differential cross section of the inclusive $\Lambda$ measurement is calculated by

$$\frac{d\sigma}{d\Omega dp} = \frac{N_{\text{yield}}^{\Lambda}(p, \cos \theta)}{N'_{\gamma} \cdot N_{\text{target}} \cdot \epsilon_{\text{acpt}}^{\Lambda}(p, \cos \theta) \cdot \eta^{\Lambda} \cdot \epsilon^{\text{common}} \cdot \epsilon^{\Lambda} \cdot 2\pi d(\cos \theta) dp}$$  \hspace{1cm} (3.54)

where $N'_{\gamma}$, $N_{\text{target}}$ and $\epsilon^{\text{common}}$ are just the same as the case of the inclusive $K^0$ measurement. Moreover, $N_{\text{yield}}^{\Lambda}$, $\epsilon_{\text{acpt}}^{\Lambda}(p, \cos \theta)$ and $\epsilon^{\Lambda}$ are the yield, the acceptance for $\Lambda \rightarrow p\pi^-$ decay mode and various efficiencies for the inclusive $\Lambda$ measurement. The $\eta^{\Lambda}$ is the branching ratio to the $p\pi^-$ decay channel by $\Lambda$.

The various efficiencies for the inclusive $\Lambda$ measurement are given as,

$$\epsilon^{\Lambda} = \epsilon_{1M}^{\Lambda} \cdot \epsilon_{\#\text{hit}}^{\Lambda} \cdot \epsilon_{\chi^2}^{\Lambda} \cdot \epsilon_{\text{hodo}}^{\Lambda} \cdot \epsilon_{\text{cdist}}^{\Lambda} \cdot \epsilon_{\text{inevi}}^{\Lambda} \cdot \epsilon_{\text{feedback}}^{\Lambda}$$  \hspace{1cm} (3.55)

where $\epsilon_{1M}^{\Lambda}$, $\epsilon_{\#\text{hit}}^{\Lambda}$, $\epsilon_{\chi^2}^{\Lambda}$, $\epsilon_{\text{hodo}}^{\Lambda}$, $\epsilon_{\text{cdist}}^{\Lambda}$ and $\epsilon_{\text{inevi}}^{\Lambda}$ are suggested the same efficiencies and normalization factors as the case of the inclusive $K^0$ measurement. though these values are different. Additionally, $\epsilon_{\text{feedback}}^{\Lambda}$, the feedback factors from the background subtractions as described in Sec. 3.4.2, is considered for the case of the inclusive $\Lambda$ measurement.
Chapter 4

Experimental results

The experiment of the $K^0$ photoproduction on the deuteron was successfully performed using a new magnetic spectrometer (NKS2) with the large acceptance in 2006 and 2007 at LNS-Tohoku. NKS2 with the expanded acceptance showed a high performance for the inclusive measurements of not only $K^0$ but also $\Lambda$. In addition, the $K^0\Lambda$ exclusive measurement was demonstrated by this experiment.

In this chapter the experimental results on the deuteron for the inclusive $K^0$ and $\Lambda$ measurements are presented. The momentum spectra for the inclusive $K^0$ measurement were compared with the previous results of NKS in Sec. 4.3.

Angular and momentum distributions

The angular and the momentum distributions for the $K^0$ and $\Lambda$ measurements are calculated as follows,

$$\frac{d\sigma}{d\Omega}_{\text{Lab}} = \frac{\iint d\sigma \cdot dpdE_\gamma}{\int dE_\gamma},$$

$$\frac{d\sigma}{dp}_{\text{Lab}} = \frac{2\pi \iint d\sigma \cdot d(\cos \theta)dE_\gamma}{\int dE_\gamma},$$

where $\frac{d\sigma}{d\Omega dp}$ is given as Eqs. (3.51) and (3.54).

Integral cross section

The integral cross sections are given by

$$\sigma = \frac{2\pi \iiint d\sigma \cdot d(\cos \theta)dpdE_\gamma}{\int dE_\gamma}.$$
4.1 Results of the inclusive $K^0$ measurement

4.1.1 Momentum spectra of the inclusive $K^0$ measurement

The inclusive momentum spectra for the $K^0$ photoproduction on the deuteron in the two photon energy regions, $0.90 < E_\gamma \leq 1.00$ GeV (a) and $1.00 < E_\gamma \leq 1.08$ GeV (b), before the subtraction of the background contributions are shown in Fig. 4.1. As described in Sec. 3.4.1, the background contributions were estimated to come from the two types (B.G.(1), B.G.(2)). The contributions of B.G.(1) and B.G.(2) are shown as the green squares and the blue triangles in each figure, respectively. These spectra are integrated for $d(\cos\theta_{K^0_{\text{Lab}}})=0.1$ bins in the laboratory system.

The momentum spectra after the subtraction of the background contributions are shown in Fig. 4.2. These spectra cover extensively in the $K^0$ production angle. The error bars show the statistical errors in these figures. The systematical uncertainties was estimated to be 11% using the standard error propagation of each systematical errors. The main components of the uncertainties come from the uncertainties of the acceptance and of the tracking efficiencies.

Figure 4.1: Momentum spectra for the inclusive $K^0$ photoproduction on the deuteron in the photon energy regions (a) from 0.90 to 1.00 GeV and (b) from 1.00 to 1.08 GeV before the background subtraction (black squares). The contributions of B.G.(1) and B.G.(2) as described in Sec. 3.4.1 are shown as green squares and blue triangles, respectively. The integral regions of the angular region in the laboratory system are displayed in the upper right of each spectrum. The error bars show the statistical errors.
4.1. RESULTS OF THE INCLUSIVE $K^0$ MEASUREMENT

Figure 4.2: Momentum spectra for the inclusive $K^0$ photoproduction on the deuteron in the photon energy regions (a) from 0.90 to 1.00 GeV and (b) from 1.00 to 1.08 GeV after the background subtraction. The error bars show the statistical errors. The systematical uncertainties were estimated to be 11%.
4.2 Results of the inclusive Λ measurement

4.2.1 Momentum spectra of the inclusive Λ measurement

The momentum spectra for the inclusive Λ measurement on the deuteron in the two photon energy regions before the subtraction of the background contributions are shown in Fig. 4.3. The background contributions were estimated using the side bands of the $p\pi^-$ invariant mass spectra. The contributions of the left and right side bands are shown as the red squares and the green triangles in each spectrum, respectively. The angular bins are $\Delta(\cos \theta_{\Lambda}^{\text{Lab}}) = 0.05$ wide in the laboratory system, in four equal steps from $\cos \theta_{\Lambda}^{\text{Lab}} = 1$ to 0.80. In these spectra, the statistical errors are represented as error bars.

The spectra after the subtraction of the background contributions are shown in Fig. 4.4. The spectra of the inclusive Λ production were obtained for the first time. The error bars show the statistical errors in these figures. The systematical uncertainties were estimated to be 14%.

\[ E_t = 0.90 - 1.00 \text{ GeV} \]

\[ E_t = 1.00 - 1.08 \text{ GeV} \]

Figure 4.3: Momentum spectra for the inclusive Λ photoproduction on the deuteron in the photon energy regions (a) from 0.90 to 1.00 GeV and (b) from 1.00 to 1.08 GeV before the background subtractions (black circles). The contributions of the left and right side bands of the $p\pi^-$ invariant mass spectra are shown as red squares and green triangles in each spectrum, respectively. The integral regions of the angular region in the laboratory system are displayed in the upper left of each spectrum. The error bars show the statistical errors.

4.2.2 Integral cross section of the inclusive Λ measurement

The integral cross section for the inclusive Λ measurement on the deuteron was obtained for the first time (see Fig. 4.5). This spectrum was integrated over the angular region of $0.9 < \cos \theta_{\Lambda}^{\text{Lab}} \leq 1.0$ in the laboratory system. The integral regions for the momentum covers the almost all Λ generating region by considering kinematics of the $K\Lambda$ reactions. These integral regions are listed in Table 4.1. In this figure the error bars show the statistical errors. The systematic uncertainties for the integral cross section were estimated to be less than 14%. The uncertainties of the photon energy were estimated to be ±10 MeV.
4.2. RESULTS OF THE INCLUSIVE $\Lambda$ MEASUREMENT

(a) $E_\gamma = 0.90\text{-}1.00$ GeV

(b) $E_\gamma = 1.00\text{-}1.08$ GeV

Figure 4.4: Momentum spectra for the inclusive $\Lambda$ photoproduction on the deuteron in the photon energy regions (a) from 0.90 to 1.00 GeV and (b) from 1.00 to 1.08 GeV after the background subtraction. The error bars show the statistical errors. The systematical uncertainties were estimated to be 14%.
Figure 4.5: Integral cross section of the present analysis for the inclusive $\Lambda$ photoproduction on the deuteron. The integral region of the angular region in the laboratory frame is $0.9 < \cos \theta_{\Lambda}^{\text{Lab}} \leq 1.0$. The error bars mean the only statistical error, and the systematic uncertainties were estimated to be 14%.

Table 4.1: Integral region of the total cross section for the inclusive $\Lambda$ photoproduction

<table>
<thead>
<tr>
<th>Energy [GeV]</th>
<th>Segment $i$</th>
<th>$\cos \theta_{K^0}^{\text{Lab}}$</th>
<th>Momentum [GeV/c]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.826 &lt; E_\gamma \leq 0.854$</td>
<td>$36.5 \leq i \leq 40$</td>
<td>0.90 - 1.00</td>
<td>0.30 - 0.80</td>
</tr>
<tr>
<td>$0.854 &lt; E_\gamma \leq 0.879$</td>
<td>$32.5 \leq i \leq 36$</td>
<td>0.90 - 1.00</td>
<td>0.30 - 0.80</td>
</tr>
<tr>
<td>$0.879 &lt; E_\gamma \leq 0.903$</td>
<td>$28.5 \leq i \leq 32$</td>
<td>0.90 - 1.00</td>
<td>0.30 - 0.80</td>
</tr>
<tr>
<td>$0.903 &lt; E_\gamma \leq 0.928$</td>
<td>$24.5 \leq i \leq 28$</td>
<td>0.90 - 1.00</td>
<td>0.30 - 0.80</td>
</tr>
<tr>
<td>$0.928 &lt; E_\gamma \leq 0.954$</td>
<td>$20.5 \leq i \leq 24$</td>
<td>0.90 - 1.00</td>
<td>0.30 - 0.90</td>
</tr>
<tr>
<td>$0.954 &lt; E_\gamma \leq 0.979$</td>
<td>$16.5 \leq i \leq 20$</td>
<td>0.90 - 1.00</td>
<td>0.30 - 0.90</td>
</tr>
<tr>
<td>$0.979 &lt; E_\gamma \leq 1.003$</td>
<td>$12.5 \leq i \leq 16$</td>
<td>0.90 - 1.00</td>
<td>0.30 - 1.00</td>
</tr>
<tr>
<td>$1.003 &lt; E_\gamma \leq 1.029$</td>
<td>$8.5 \leq i \leq 12$</td>
<td>0.90 - 1.00</td>
<td>0.30 - 1.00</td>
</tr>
<tr>
<td>$1.029 &lt; E_\gamma \leq 1.055$</td>
<td>$4.5 \leq i \leq 8$</td>
<td>0.90 - 1.00</td>
<td>0.30 - 1.10</td>
</tr>
<tr>
<td>$1.055 &lt; E_\gamma \leq 1.080$</td>
<td>$1 \leq i \leq 4$</td>
<td>0.90 - 1.00</td>
<td>0.30 - 1.10</td>
</tr>
</tbody>
</table>
4.3  Comparison with the previous experiment

The experimental results of the $K^0$ photoproduction on the carbon [92] and the deuteron [94] have been published from NKS. In the case of NKS2, the experimental data of the $K^0$ photoproduction on the carbon were hardly taken. Here the inclusive $K^0$ momentum spectra of NKS2 on the deuteron in the energy region of $0.9 < E_\gamma \leq 1.0$ GeV and in the angular region of $0.9 < \cos \theta_{K^0}^{\text{Lab}} \leq 1.0$ were compared with the previous results.

Figure 4.6 shows the comparison of the $K^0$ momentum spectra. The red squares and the black circles in this figure represent the results of NKS and NKS2, respectively. The error bars of each spectrum represent the statistical error. These two results using two different spectrometers, NKS and NKS2, consist within statistical errors. In the high momentum region of $p_{K^0}^{\text{Lab}} > 0.5$ GeV/c, the results of NKS (red squares) have the huge errors. It causes that the detector configuration of NKS did not cover in the forward (see Fig. 1.5). On the other hand, the statistical errors of this region in NKS2 become smaller. The decrease of errors in this region has a significant contribution to compare the results with the theoretical calculations.

Figure 4.6: Comparison of the $K^0$ momentum spectra between the results of NKS (red squares) and those of NKS2 (black circles) on the deuteron in the energy region of $0.9 < E_\gamma \leq 1.0$ GeV and in the angular region of $0.9 < \cos \theta_{K^0}^{\text{Lab}} \leq 1.0$. The error bars of each spectrum represent the statistical error.

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†Comparing the two results, the trivial mistake in the photon flux normalization was found in the NKS results. The erratum has been prepared. Here the corrected results are introduced.
Chapter 5

Discussion

5.1 Comparison with the results of the $K^+\Lambda$ reaction

5.1.1 Comparison of angular distributions

In this analysis, the momentum spectra of the $\gamma d \rightarrow K^0 X$ reaction in the laboratory system were obtained. Although the angular distributions of the $\gamma p \rightarrow K^+\Lambda$ reaction in the center of mass (c.m.) system were generally provided by the other groups, the present results cannot be directly compared with the $K^+\Lambda$ reaction.

To show the angular distributions of the elementary $K^0\Lambda$ reaction preferred by the present results, a phenomenological parametrization in the c.m. system, named PH(a), was used,

$$\frac{d\sigma}{d\Omega_{CM}} = \sqrt{s - s_0} (1 + e_0(s - s_0)) \cdot (a_0 + a_1 \cos(\theta_{CM}^{K^0}) + a_2 \cos^2(\theta_{CM}^{K^0})).$$  \hspace{1cm} (5.1)

Here $\theta_{CM}^{K^0}$ and $s$ are the $K^0$ production angle in the c.m. system and the Mandelstam variable ($s_0=2.603$ GeV$^2$: $K^0\Lambda$ threshold), respectively. The $e_0$, $a_0$, $a_1$, $a_2$ and $a_3$ represent the fitting parameters. The $K^0$ momentum spectra with the distributions of Eq. (5.1) were calculated using the Monte-Carlo simulation using the following assumptions,

- the $\gamma n \rightarrow K^0\Lambda$ reaction of a quasi-free process,
- the angular distribution in the c.m. system with Eq. (5.1),
- Hulthén wave function as Fermi momentum of a neutron in the deuteron.

The simultaneous fit was done for the $K^0$ momentum spectra obtained in the experimental data in these two kinematical regions,

1. $0.9 < E_\gamma \leq 1.0$ GeV and $0.9 < \cos\theta_{K^0}^{Lab} \leq 1.0$ (see Fig. 5.1(a)),
2. $0.9 < E_\gamma \leq 1.0$ GeV and $0.8 < \cos\theta_{K^0}^{Lab} \leq 0.9$ (see Fig. 5.1(b)).

The contributions of the $\Sigma$ production channels are expected to be small in this energy region due to the photon energy below threshold. Figure 5.1 shows the best-fit results with the parameters. The best-fit parameters for PH(a) were obtained: $e_0=2.31\pm1.32$, $a_0=1.218\pm0.257$, $a_1=-0.517\pm0.120$, and $a_2=-0.733\pm0.256$. Then the angular distributions of $K^0$ in the $K^0\Lambda$ reaction are obtained.

Figure 5.2 shows the $K^0$ angular distributions at the photon energy of 0.97 GeV, where the best-fit curves are also depicted assuming the functions with higher-order distributions in
addition to PH(a). The red line represents the results of PH(a) and the hatching region is 1σ from the fitting result. The black dash, green dot and cyan dash-dot lines show the angular distributions by fitting results assuming PH(b), PH(c) and PH(d) as follows,

\[
\frac{d\sigma}{d\Omega_{CM}} = \sqrt{s - s_0} \left( 1 + e_0(s - s_0) \right) \\
\cdot \left( a_0 + a_1 \cos(\theta_{K_0^{\pm}}) + a_2 \cos^2(\theta_{K_0^{\pm}}) + a_3 \cos^3(\theta_{K_0^{\pm}}) \right) \quad \text{(PH(b))}, \quad (5.2)
\]

\[
\frac{d\sigma}{d\Omega_{CM}} = \sqrt{s - s_0} \left( 1 + e_0(s - s_0) + e_1(s - s_0)^2 \right) \\
\cdot \left( a_0 + a_1 \cos(\theta_{K_0^{\pm}}) + a_2 \cos^2(\theta_{K_0^{\pm}}) \right) \quad \text{(PH(c))}, \quad (5.3)
\]

\[
\frac{d\sigma}{d\Omega_{CM}} = \sqrt{s - s_0} \left( 1 + e_0(s - s_0) + e_1(s - s_0)^2 \right) \\
\cdot \left( a_0 + a_1 \cos(\theta_{K_0^{\pm}}) + a_2 \cos^2(\theta_{K_0^{\pm}}) + a_3 \cos^3(\theta_{K_0^{\pm}}) \right) \quad \text{(PH(d))}, \quad (5.4)
\]

where \(e_1\) and \(a_3\) are higher-order contributions. The difference of the functions does not effect the final angular distributions. These angular distributions have an enhancement in the backward region. However, these distributions represent the different shapes from the suggestion of the NKS results (PH1). The present results suggest the larger contributions of the \(p\)-wave. The distribution of PH1 was determined by only the \(K^0\) momentum spectra in the angular region of \(0.9 < \cos \theta_{K^0_{\text{Lab}}}/E_{K^0} \leq 1.0\) in the previous NKS experiment. On the other hand, our results cover the larger angular region in the c.m. system than the NKS results in order to fit two momentum spectra with different angular regions simultaneously. The present results suggest the precise angular distributions of the \(K^0\Lambda\) production in the c.m. system.

Figure 5.3 shows the comparison of the angular distributions in the c.m. system between the \(K^0\Lambda\) and \(K^+\Lambda\) reactions. The red line shows the distribution of the \(\gamma n \rightarrow K^0\Lambda\) reaction in the energy of \(E_\gamma = 0.988\) GeV indicated by PH(a). The hatching region represents the 1σ. The black squares and the cyan circles represent that of the \(\gamma p \rightarrow K^+\Lambda\) reaction in the energy region of \(E_\gamma = 0.975\)–1.0 GeV from SAPHIR [34] and in the energy of \(E_\gamma = 0.994\) GeV from CLAS [42], respectively. The black dash line is the best-fit result using Legendre polynomials for the SAPHIR data (see [34]). The angular distributions of the \(K^0\Lambda\) and \(K^+\Lambda\) reactions in the c.m. system show contrast shapes. The \(K^0\Lambda\) reaction has the larger cross section in the backward while the \(K^+\Lambda\) shows the slight forward peaking.

Figure 5.1: Fitting results of the \(K^0\) momentum spectra using a phenomenological parametrization function given by Eq. (5.1).
5.1. COMPARISON WITH THE RESULTS OF THE $K^+\Lambda$ REACTION

Figure 5.2: Angular distributions of the $K^0\Lambda$ reaction depending on the assuming functions with high order contributions at the photon energy of 0.970 GeV. The red line represents the results of PH(a) (Eq. (5.1)) and the hatching region is 1 $\sigma$ from the fitting result. The black dash and green dot and cyan dash-dot lines show the angular distributions by fitting results using the assuming PH(b) (Eq. (5.2)) PH(c) (Eq. (5.3)) and PH(d) (Eq. (5.4)), respectively.

Figure 5.3: Comparison of the angular distributions in the c.m. system with the $K^+\Lambda$ reaction. The red line shows the distribution of the $K^0\Lambda$ reaction in the energy of $E_\gamma=0.988$ GeV indicated by the present results. The black squares and the cyan circles represent that of the $\gamma p \rightarrow K^+\Lambda$ reaction in the energy region of $E_\gamma=0.975$–1.0 GeV from SAPHIR [34] and in the energy of $E_\gamma=0.994$ GeV from CLAS [42], respectively. The black dash line is the fitting results using Legendre polynomials for the SAPHIR data (see [34]).
5.1.2 Comparison of total cross sections

The total cross section of the $\gamma n \to K^0 \Lambda$ reaction ($\sigma_{Total}^{K^0\Lambda}$) was estimated from the $\Lambda$ integral cross section on the deuteron ($\sigma_{Integral}^{\gamma d \to \Lambda X}$) as follows,

$$\sigma_{Total}^{K^0\Lambda} = \left( \sigma_{Integral}^{\gamma d \to \Lambda X} - \sigma_{Integral}^{\gamma d \to K^+\Lambda n} \right) \cdot \frac{\sigma_{Total}^{\gamma d \to K^0\Lambda p}}{\sigma_{Integral}^{\gamma d \to K^0\Lambda p}}$$

where $\sigma_{Integral}^{\gamma d \to K^+\Lambda n}$ is the integral cross section of the $\gamma d \to K^+\Lambda n$ reaction. The $\sigma_{Integral}^{\gamma d \to K^0\Lambda p}$ and $\sigma_{Total}^{\gamma d \to K^0\Lambda p}$ are the integral and total cross sections of the $\gamma d \to K^0\Lambda p$ reaction, respectively. Here, the integral regions are over the angular region of $0.9 < \cos \theta_{\text{Lab}} \Lambda \leq 1.0$ in the laboratory system. The present results of the $\Lambda$ integral cross section ($\sigma_{Integral}^{\gamma d \to \Lambda X}$) are shown in Fig. 4.5.

The $\sigma_{Integral}^{\gamma d \to K^+\Lambda n}$, $\sigma_{Integral}^{\gamma d \to K^0\Lambda p}$ and $\sigma_{Total}^{\gamma d \to K^0\Lambda p}$ were estimated assuming the following 4 cases (see Figs. 5.11 and 5.13),

1. the Kaon-MAID model,
2. the SLA model with the $r_{K^1K\gamma} = -1.0$ value,
3. the SLA model with the $r_{K^1K\gamma} = -1.5$ value,
4. $\gamma d \to K^+\Lambda n$ reaction by Kaon-MAID and $\gamma d \to K^0\Lambda p$ reaction by Eq. (5.1),

Figure 5.4 shows the total cross sections of the $K^0\Lambda$ reaction estimated by Eq. (5.5). The red, green, cyan and black markers represent those calculated assuming (1), (2), (3) and (4), respectively. These cross sections in the figure are possibly about 20% larger at the photon energy of 1.1 GeV, because this estimation of Eq. (5.5) does not include the $\Sigma^0$ contributions. However, the $\Sigma^0$ contributions are negligibly small in the photon energy of $<1.0$ GeV.

Figure 5.5 shows the comparison of total cross sections between the $K^0\Lambda$ and $K^+\Lambda$ reactions. The $K^0\Lambda$ total cross sections, which were estimated from the $\Lambda$ integral cross section using Eq. (5.5) and the calculations of (1), were represented as the red circles in the figure. The total cross sections of the $\gamma p \to K^+\Lambda$ reaction measured by the SAPHIR group are shown by the black squares [34] and the green triangles [32]. These two data for the $K\Lambda$ productions agree each other in the present energy region reasonably well. It suggests that the energy dependence of the $\gamma n \to K^0\Lambda$ reaction is almost the same as that of the $\gamma p \to K^+\Lambda$ near the threshold.
5.1. COMPARISON WITH THE RESULTS OF THE $K^+\Lambda$ REACTION

Figure 5.4: Total cross sections of the $\gamma n \rightarrow K^0\Lambda$ reaction estimated by Eq. (5.5). The red, green, cyan and black markers show those assuming the calculations (1), (2), (3) and (4), respectively. (see text) The Lines are the systematic errors. It is to be noted that this estimation does not include the $\Sigma^0$ contributions.

Figure 5.5: Comparison of the total cross sections with the $K^+\Lambda$ reaction. The present results (red circles) of the $K^0\Lambda$ production were estimated from the $\Lambda$ integral cross section using Eq. (5.5) and the theoretical calculations of the Kaon-MAID model. The total cross sections of the $K^+\Lambda$ production on the proton from SAPHIR [32, 34] (black squares, green triangles) are shown. The error bars show the statistical error. It is to be noted that this estimation does not include the $\Sigma^0$ contributions.
5.2 Comparison with the theoretical calculations

5.2.1 Theoretical calculations

5.2.1.1 Elementary amplitude for the $K^+\Lambda$ process

Elementary amplitude of the isobar models

Here, two recent isobar models, Kaon-MAID \cite{45,63} and Saclay-Lyon A (SLA) \cite{67}, are explained for the comparison with the present results. The Lorentz invariant matrix elements in the frame of the isobar models are expressed as follows:

$$M_{fi} = M(Born) + \sum_{N^*} M_s + \sum_{K^*,K_1} M_t + \sum_{Y^*} M_u.$$ (5.6)

The Born terms contribute basically. Additionally, the different resonances by each approach of the isobar models are introduced in the particle exchanges of $s$-, $t$- and $u$-channels. The resonances which are taken into account in the Kaon-MAID and SLA models for the $K\Lambda$ process are listed in Table 5.1.

<table>
<thead>
<tr>
<th>$I(J^{P})$</th>
<th>Kaon-MAID</th>
<th>SLA</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Born terms</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$s$-channel</td>
<td>$N$ ($p$ or $n$) $\frac{1}{2}(\frac{1}{2}^+)$</td>
<td>$\times$</td>
</tr>
<tr>
<td>$t$-channel</td>
<td>$K$ $\frac{1}{2}(0^-)$</td>
<td>$\times$</td>
</tr>
<tr>
<td>$u$-channel</td>
<td>$\Lambda$ $0(\frac{1}{2}^-)$</td>
<td>$\times$</td>
</tr>
<tr>
<td></td>
<td>$\Sigma$ $1(\frac{1}{2}^+)$</td>
<td>$\times$</td>
</tr>
<tr>
<td><strong>resonance term</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$t$-channel</td>
<td>$K^*(892)$ $\frac{1}{2}(1^-)$</td>
<td>$\times$</td>
</tr>
<tr>
<td></td>
<td>$K_1(1270)$ $\frac{1}{2}(1^+)$</td>
<td>$\times$</td>
</tr>
<tr>
<td>$s$-channel</td>
<td>$S_{11}(1565)$ $\frac{1}{2}(\frac{1}{2}^+)$</td>
<td>$\times$</td>
</tr>
<tr>
<td></td>
<td>$P_{11}(1710)$ $\frac{1}{2}(\frac{1}{2}^+)$</td>
<td>$\times$</td>
</tr>
<tr>
<td></td>
<td>$P_{13}(1720)$ $\frac{1}{2}(\frac{3}{2}^+)$</td>
<td>$\times$</td>
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<td></td>
<td>$D_{13}(1895)$ $\frac{1}{2}(\frac{3}{2}^-)$</td>
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<td>$\times$</td>
</tr>
<tr>
<td></td>
<td>$P_{11}(1660)$ $1(\frac{3}{2}^-)$</td>
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<tr>
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</tbody>
</table>

The Kaon-MAID model is a latest isobar model which can account for kaon productions of six isospin channels without the final-state interaction (meson-baryon rescattering processes). This model for the $K\Lambda$ process includes the standard Born terms and four nucleon resonances, $S_{11}(1650)$, $P_{11}(1710)$, $P_{13}(1720)$, $D_{13}(1895)$ in the $s$-channel and two meson states, $K^*(892)$, $K_1(1270)$, in the $t$-channel, no hyperon resonance in the $u$-channel. Three nucleon resonances, $S_{11}(1650)$, $P_{11}(1710)$, $P_{13}(1720)$, are found to be dominant in the reaction. The $D_{13}(1895)$ resonance\textsuperscript{†}, which is predicted to have a significant $K\Lambda$ decay width by the constituent quark

\textsuperscript{†}Unconfirmed mass: The $D_{13}(1900)$ and the $D_{13}(1960)$ resonances suggest the same state.
model calculation [1], is a candidate of a missing resonance. This resonance reproduces the bump structure of the total cross section of the $\gamma p \rightarrow K^+\Lambda$ reaction observed by the SAPHIR group. For the $K\Sigma$ process, the $S_{11}(1900)$ and $P_{31}(1910)$ resonances are included. The hadronic form factors with a dipole shape are introduced in this model,

$$ F_{\text{Dipole}}(x) = \frac{\Lambda_{\text{res}}^4}{\Lambda_{\text{res}}^4 + (x - m_{N,N^*}^2)^2}, \quad (5.7) $$

where $x$, $m_{N,N^*}$ and $\Lambda_{\text{res}}$ are the Mandelstam variable ($x = s, t, u$), the mass of the nucleon or the resonance and the cutoff value, respectively. An additional contact term is considered in order to restore the gauge invariance violated by this form factor as suggested by H. Haberzettl [69, 99]. The parameters of this model were obtained by fitting the old dataset as Ref. [71] and the SAPHIR data [32, 33].

In the Saclay-Lyon (SL) model [65], higher spin resonances in the $s$-channel and hyperon resonances in the $u$-channel are introduced. The $\gamma p \rightarrow K^+\Lambda$ and $ep \rightarrow e'K^+\Lambda$ processes are applied up to the photon energy of 1.5 GeV. The point-like particles are assumed in hadronic vertices. The SLA model is a simplified version of the SL model omitted $P_{11}(1440)$ and $D_{15}(1675)$ resonances. This model includes the Born terms and only one nucleon resonance, $P_{11}(1710)$, in the $s$-channel and two kaon resonances, $K^*(892)$ and $K_1(1270)$, in the $t$-channel and four hyperon resonances, $S_{01}(1405)$ and $S_{01}(1670)$ and $P_{01}(1810)$ and $P_{11}(1660)$, in the $u$-channel. The parameters were fitted to the same old dataset [71] and the first results from SAPHIR by M. Bockhorst et al. [100]

### Elementary amplitude of RPR model

As described in the introduction, the “Regge-plus-resonance” (RPR) approach is the hybrid model which is extended toward the resonance region (around $\sqrt{s} \sim 2$ GeV) by adding the contribution of $s$-channel resonances to Regge theory. The Lorentz invariant matrix elements for $K^+\Lambda$ photoproductions are expressed as follows,

$$ M_{fi} = M_{\text{Regge}}^{K^+}(494) + M_{\text{Regge}}^{K^+\Lambda}(892) + M_{\text{Feyn}}^{\text{elec}} \times P_{\text{Regge}}^{K^+}(494) \times (t - m_{K^+}^2) + \sum_{N^*} M_s, \quad (5.8) $$

where 1st, 2nd and 3rd terms are in the framework of Regge theory and 4th term is adding the resonances contributions. This model have been developed for not only the $K\Lambda$ process [84, 85] but also the $K\Sigma$ [86, 87].

The Regge approach of the part of the amplitudes is aimed at the forward region ($|t| \approx 0$) description of the process due to Regge part based on the $t$-channel exchange [82, 101]. The parameters for the Regge amplitudes were fitted against the high-energy observables [16]. The $K^+(498)$ Regge-trajectory in the $t$-channel diagrams break the gauge invariance. Therefore, the electric part of the $s$-channel Born term is added to restore gauge invariance for the proton target. In the case of the $\gamma n \rightarrow K^+\Sigma^-$ reaction, the electric part of the $u$-channel Born term is adopted instead of that of the $s$-channel.

Having fitted the Reggeized background amplitude, the nuclear resonances in the $s$-channel diagram are added. The well-known resonances of $S_{11}(1650)$, $P_{11}(1710)$, $P_{13}(1720)$ and the two-star resonance of $P_{13}(1900)$ in PDG [90] are considered. In addition, The unobserved $D_{13}(1900)$ resonance, which is introduced as $D_{13}(1895)$ resonance in the Kaon-MAID model, is added to describe the $K^+\Lambda$ reaction of both photo and electroproduction data [84, 88]. On the other hand, for the $\Sigma$ production the resonances identifying the $S_{11}(1650)$, $P_{11}(1710)$, $P_{13}(1720)$,
CHAPTER 5. DISCUSSION

\( P_{13}(1900), D_{33}(1700), S_{31}(1900), P_{31}(1910) \) and \( P_{33}(1920) \) are added as essential contributions. Moreover, in the other approach a relevance/importance of the \( P_{13}(1900) \) and \( S_{31}(1900) \), which are two-star resonance in PDG, is investigated \[87\].

In this approach, the hadronic farm factor, \( F(s) \), with a gaussian shape at the hadronic vertices are introduced as follows,

\[
F_{\text{Gauss}}(s) = \exp \left( -\frac{(s - m_{N^*}^2)}{\Lambda_{\text{res}}^4} \right),
\]

where the \( s \) and \( m_{N^*} \) are the Mandelstam variable and the mass of the resonance, respectively. The \( \Lambda_{\text{res}} \) is the cutoff value (typically 1600 MeV). This form factor is considered instead of the standard form factor with a dipole shape so that the resonance amplitudes should vanish at the high energy.

5.2.1.2 Relation between \( K^+ \) and \( K^0 \) photoproduction process

The phenomenological approaches assumes some relations, such as the isospin symmetry, to suppress the number of fitting parameters and to constrain the values of those. Although some contents overlap as described in Sec. 1.3.1, the relationships between \( K^+ \) and \( K^0 \) photoproductions are summarized.

**Hadronic coupling**

To relate the hadronic coupling constants among the \( KA \) channel (or various isospin channels), the isospin symmetry is assumed as follows:

**Born term:**

\[
g_{K^+\Lambda p} = g_{K^0\Lambda n}, \tag{5.10}
g_{K^+\Sigma^0 p} = -g_{K^0\Sigma^0 n} = g_{K^0\Sigma^+ p}/\sqrt{2} = -g_{K^+\Sigma^- n}/\sqrt{2}, \tag{5.11}
g_{K^+\Sigma^+ \Delta^+} = g_{K^0\Sigma^0 \Delta^0} = -\sqrt{2}g_{K^0\Sigma^+ \Delta^+} = \sqrt{2}g_{K^+\Sigma^- \Delta^0}, \tag{5.12}
\]

**Resonance term (s-channel):**

\[
g_{K^+\Lambda N^{*+}} = g_{K^0\Lambda N^{*0}}, \tag{5.13}
g_{K^+\Sigma^0 N^{*+}} = -g_{K^0\Sigma^0 N^{*0}} = g_{K^0\Sigma^+ N^{*+}}/\sqrt{2} = -g_{K^+\Sigma^- N^{*0}}/\sqrt{2}, \tag{5.14}
g_{K^+\Sigma^0 \Delta^{*+}} = g_{K^0\Sigma^0 \Delta^{*0}} = -\sqrt{2}g_{K^0\Sigma^+ \Delta^{*+}} = \sqrt{2}g_{K^+\Sigma^- \Delta^{*0}}, \tag{5.15}
\]

**Resonance term (t-channel):**

\[
g_{V,T,K^+\Lambda p} = g_{V,T,K^0\Lambda n}, \tag{5.16}
\]

**Resonance term (u-channel):**

\[
g_{K^+\Lambda^* p} = g_{K^0\Lambda^* n}, \tag{5.17}
g_{K^+\Sigma^0 p} = -g_{K^0\Sigma^0 n} = g_{K^0\Sigma^+ p}/\sqrt{2} = -g_{K^+\Sigma^- n}/\sqrt{2}, \tag{5.18}
\]

where \( N^*, \Delta^*, \Lambda^*, \Sigma^* \) and \( K^* \) are isospin \( \frac{1}{2}, \frac{3}{2} \) nucleon resonances, isosinglet, isotriplet hyperon resonances and vector kaon resonances, respectively.
5.2. COMPARISON WITH THE THEORETICAL CALCULATIONS

Photo-coupling in the s-channel

In the electromagnetic coupling, the relation between helicity amplitudes, \( A_j^N \), and transition moments is obtained as follows:

\[
A_{1/2}^N = \pm \frac{e}{2m_N} \left( \frac{m_{N^*}^2 - m_N^2}{2m_N} \right)^{1/2} \kappa_{N^*N\gamma} \quad \text{(for spin } \frac{1}{2} \text{)}, \tag{5.19}
\]

\[
A_{1/2}^N = \frac{e}{4m_N^*} \sqrt{\frac{m_{N^*}^2 - m_N^2}{3m_N}} \left( \pm \kappa_{N^*N\gamma}^{(1)} - \frac{m_N (m_{N^*} \mp m_N)}{4m_N^2} \kappa_{N^*N\gamma}^{(2)} \right) \quad \text{and}
\]

\[
A_{3/2}^N = \frac{e}{4m_N} \sqrt{\frac{m_{N^*}^2 - m_N^2}{m_N}} \left( \pm \kappa_{N^*N\gamma}^{(1)} \mp \frac{m_N \mp m_{N^*}}{4m_N^2} \kappa_{N^*N\gamma}^{(2)} \right) \quad \text{(for spin } \frac{3}{2} \text{)}, \tag{5.20}
\]

where the upper and the lower signs correspond to the parity of each resonance. Therefore, the relation between the helicity amplitudes and the transition moments is given by

\[
\frac{\kappa_{N^*n\gamma}}{\kappa_{N^*p\gamma}} = \frac{A_{1/2}^n}{A_{1/2}^p} \quad \text{(for spin } \frac{1}{2} \text{)}, \tag{5.21}
\]

\[
\begin{align*}
\frac{\kappa_{N^*n\gamma}^{(1)}}{\kappa_{N^*p\gamma}^{(1)}} &= \frac{\sqrt{3} A_{1/2}^n \pm A_{3/2}^n}{\sqrt{3} A_{1/2}^p \pm A_{3/2}^p} \\
\frac{\kappa_{N^*n\gamma}^{(2)}}{\kappa_{N^*p\gamma}^{(2)}} &= \frac{\sqrt{3} A_{1/2}^n - (m_N/m_{N^*}) A_{3/2}^n}{\sqrt{3} A_{1/2}^p - (m_N/m_{N^*}) A_{3/2}^p} \quad \text{(for spin } \frac{3}{2} \text{).} \tag{5.22}
\end{align*}
\]

The conversion of the photo-couplings requires knowledge of the helicity amplitudes. Beyond the second resonance region, the helicity amplitudes of each resonance are either unknown or poorly constrained by the pion production data. Especially, Kaon-MAID model and RPR model introduce a missing resonance (\( D_{13}(1895) \)). In Kaon-MAID model, the transition based on the prediction of the quark model is adopted. On the other hand, transition moments are varied between \(-2\) and \(+2\) in the approach of RPR model. The helicity amplitudes are summarized in Table 5.2.

Photo-coupling in the t-channel

To calculate the \( K^0 \) photoproduction in the isobar approaches, the charged transition moments (\( \kappa_{K^+K^+} \)), which was obtained by the fitting of \( K^+ \) photoproduction, have to be replaced by the neutral transition moments (\( \kappa_{K^0K^0} \)). The transition moments can be estimated through the radiative decay widths of kaon resonances:

\[
\Gamma_{K^* \rightarrow K\gamma} = \frac{1}{24} \frac{|\kappa_{K^*K\gamma}|^2}{4\pi M^2} \left[ m_{K^*} \left( 1 - \frac{m_K^2}{m_{K^*}^2} \right) \right]^3, \tag{5.23}
\]

where \( K^* \) means \( K^*(892) \) and \( K_1(1270) \), and \( M \) is a mass scale (here 1 GeV) to make the transition moment (\( \kappa_{K^*K\gamma} \)) dimensionless. For the \( K^*(892) \) case, the decay width for \( K^*(892) \)
Table 5.2: Helicity amplitude of the nucleon resonances

<table>
<thead>
<tr>
<th>$A^p_{1/2}$ [GeV$^{-1/2}$]</th>
<th>$S_{11}(1650)$</th>
<th>$P_{11}(1710)$</th>
<th>$P_{13}(1720)$</th>
<th>$P_{13}(1900)$†</th>
</tr>
</thead>
<tbody>
<tr>
<td>+0.053 ± 0.016</td>
<td>+0.009 ± 0.022</td>
<td>+0.018 ± 0.030</td>
<td>−0.017</td>
<td></td>
</tr>
<tr>
<td>−0.015 ± 0.021</td>
<td>−0.002 ± 0.014</td>
<td>+0.001 ± 0.015</td>
<td>−0.016</td>
<td></td>
</tr>
<tr>
<td>−0.019 ± 0.020</td>
<td>+0.031</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>−0.029 ± 0.061</td>
<td>−0.002</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

† two-star resonance, the errors are not reported in PDG

were already well-established, $\Gamma_{K^+\to K^+\gamma} = 50 \pm 5$ keV and $\Gamma_{K^0\to K^0\gamma} = 117 \pm 10$ keV [90]. Here, the ratio of the transition moments can be determined as:

$$r_{K^+K\gamma} = \frac{\kappa_{K^0K^0\gamma}}{\kappa_{K^+K^+\gamma}} = \sqrt{\frac{\Gamma_{K^0\to K^0\gamma}}{\Gamma_{K^+\to K^+\gamma}}} = -1.53,$$

(5.24)

where the relative sign is extracted using the quark model [102]. On the other hand, the decay width for $K_0^0(1270)$ were measured but that for $K_1^+(1270)$ were not. Thus the ratio $r_{K_1K\gamma}$ has to be taken account as a free parameter. In Kaon-MAID model, the parameters were fitted using not only the $K^+\Lambda$ photoproductions but also the $K^0\Sigma^+$ and $K^+\Sigma^0$ photoproductions. Then, the $r_{K_1K\gamma}$ ratio was determined from the comparison of the fitting parameters in the $K^0\Sigma^+$ and $K^+\Sigma^0$ channels. The value of the $r_{K_1K\gamma}$ ratio is obtained to be $-0.4474$. On the other hand, the parameters in SLA model were fitted using only the $K^+\Lambda$ dataset. Thus the $r_{K_1K\gamma}$ ratio cannot be determined from the original model. Therefore, the $r_{K_1K\gamma}$ ratio should be considered as a free parameter in the calculation of the $K^0$ photoproduction.

To calculate the $K^0$ photoproduction on RPR approach, two modifications of the background amplitude are required. The $K(494)$ trajectory exchange is not contributed in the $t$-channel diagram. On the other hand, the transition moment of the $K^0\Sigma^+$ exchange was optimized using the $K^0\Sigma^+$ dataset [35,38,103] ($\kappa_K\kappa_{K^0\gamma}/\kappa_{K^+\gamma} = 0.05 \pm 0.01$).

### Photo-coupling in the u-channel

In the hyperon resonance exchange of $u$-channel, the photo-couplings of the $K^0\Lambda$ reaction are the same as those of the $K^+\Lambda$ reaction.

#### 5.2.1.3 Deuteron wave function

The differential cross sections of the inclusive $K^0$ and $\Lambda$ photoproductions on the deuteron are calculated by P. Bydžovský in isobar models and by P. Vancraeyveld in RPR model. Both these calculations are based on the impulse approximation but the final-state interaction (FSI), here FSI means not only $Y\Delta$ and $K\Xi$ scattering effect but also the pion-mediated process, is ignored in both calculations. There is a report that the $Y\Delta$ interaction is important for kaon photoproductions on the deuteron near the threshold, especially for the exclusive process [104–
However, the effects of FSI are negligible small for the inclusive process and the quality of the present result does not allow us to see such small effects. Moreover, a part of KY rescattering effect is absorbed in the coupling constants of the elementary amplitude and the KN interaction is weak on the hadron scale. Therefore, even if FSI is not involved in the calculations, these calculations are approximately allowed as good approach for the present results.

In the calculations of isobar models on the deuteron, the inclusive cross sections are compared with a simple spectator model calculation in the plane wave impulse approximation with a spectator nucleon by P. Bydžovský [108]. The energy of the target nucleon \( N \) is given by \( E_N = m_d - E_{N'} = E_{K^0} + E_{\Lambda} - E_{\gamma} \) for the off-shell approximation, to satisfy energy conservation in the elementary process, and by \( E_N = \sqrt{m_N^2 + p_N^2} \) for the on-shell approximation. The effective mass of the target nucleon is determined as \( \tilde{m}_N = \sqrt{p_{\mu} p_{\mu}} \) and \( p_N = -p_{N'} \) momentum distribution of the target nucleon is described by the non-relativistic Bonn deuteron wave function OBEPQ (one boson exchange potential in q space) [109]. The difference in results caused by employing the on- and off-shell approximations and the various deuteron wave functions are found to be small or negligible in the present kinematical region [108]. In the following analysis, off-shell approximation is used.

The inclusive cross section of RPR model on the deuteron are calculated within the relativistic plane wave impulse approximation (RPWIA) by P. Vancraeyveld [85]. The relativistic wave functions obtained with the WJC-1 solution [110, 111] and the deuteron function presented in Ref. [112] are adopted.
5.2.1.4 Results of the theoretical calculations

Theoretical calculations of the $K^0$ photoproduction

Figure 5.6 shows the $K^0$ momentum spectra of the $\gamma d \rightarrow K^0\Lambda p$ reaction predicted by the theoretical calculations based on the isobar models. These spectra of the angular region of $d(\cos\theta_{K^0}^{\text{Lab}}) = 0.1$ are averaged in the photon energy regions (a) from 0.90 to 1.00 GeV (lower) and (b) from 1.00 to 1.08 GeV (higher). In the case of the SLA model, the spectra were calculated for the ratio $r_{K_1K^0\gamma}$ from $-3.0$ to $-1.0$ by 0.5 step.

The $K^0$ momentum spectra predicted by the RPR model are shown in Fig. 5.7. The distributions are averaged in the angular range of $0.9 < \cos\theta_{K^0}^{\text{Lab}} \leq 1.0$ of the laboratory frame and in the lower energy region.

![Figure 5.6: $K^0$ momentum spectra of the $\gamma d \rightarrow K^0\Lambda p$ reaction predicted by the theoretical calculations based on the Kaon-MAID (black lines) and SLA models in the photon energy region from 0.90 to 1.00 GeV and in the angular region of 0.9 $\leq \cos\theta_{K^0}^{\text{Lab}} \leq 1.0$.](image1)

![Figure 5.7: $K^0$ momentum spectra of the $\gamma d \rightarrow K^0\Lambda p$ reaction predicted by the RPR model in the photon energy region from 0.90 to 1.00 GeV and in the angular region of $0.9 < \cos\theta_{K^0}^{\text{Lab}} \leq 1.0$.](image2)
5.2. COMPARISON WITH THE THEORETICAL CALCULATIONS

Theoretical calculations of the Λ photoproduction

Figures 5.8 shows Λ momentum spectra of the $\gamma d \rightarrow K^0\Lambda p$ and $\gamma d \rightarrow K^+\Lambda n$ reactions predicted by the theoretical calculations based on the Kaon-MAID model. Figure 5.9 shows those based on the SLA model. These spectra of the angular region of $d(\cos\theta_{\Lambda \text{lab}}) = 0.05$ are averaged in the (a) lower and (b) higher energy regions. The Λ momentum spectra adding the $\gamma d \rightarrow K^0\Lambda p$ and $\gamma d \rightarrow K^+\Lambda n$ reactions with the Kaon-MAID and SLA models are shown in Fig. 5.10. The ratio $r_{K_1K_\gamma}$ of the SLA model is taken account from $-3.0$ to $-1.0$ by 0.5 step.

Figure 5.8: Λ momentum spectra of $\gamma d \rightarrow K^+\Lambda n$ (black lines) and the $\gamma d \rightarrow K^0\Lambda p$ (red dash lines) reactions predicted by the theoretical calculations based on the Kaon-MAID model in the photon energy region (a) from 0.90 to 1.00 GeV and (b) from 1.00 to 1.08 GeV.

Figure 5.9: Λ momentum spectra of the $\gamma d \rightarrow K^+\Lambda n$ (black lines) and $\gamma d \rightarrow K^0\Lambda p$ reactions predicted by the theoretical calculations based on the SLA model in the photon energy region (a) from 0.90 to 1.00 GeV and (b) from 1.00 to 1.08 GeV. The $r_{K_1K_\gamma}$ values are displayed in the figure.
Figure 5.10: Λ momentum spectra adding the γd → K0Λp and γd → K+Λn reactions predicted by the Kaon-MAID (black lines) and SLA models, in the photon energy region (a) from 0.90 to 1.00 GeV and (b) from 1.00 to 1.08 GeV. The rK1Kγ values are displayed in the figure.

Figure 5.11 shows the integral cross sections of the γd → K0Λp and γd → K+Λn reactions over the angular region of 0.9< cos θΛLab ≤1.0 predicted by (a) the Kaon-MAID and (b) SLA models. The Λ integral cross sections, which add those of the γd → K0Λp reaction to those of the γd → K+Λn with the isobar models, are shown in Fig. 5.12. Figure 5.13 shows The total cross sections of the γd → K0Λp and γd → K+Λn reactions predicted by (a) the Kaon-MAID and (b) SLA models. The ratios between the total cross sections and the integral cross sections (0.9< cos θΛLab ≤1.0) for the γd → K0Λp and γd → K+Λn reactions indicated by (c) the Kaon-MAID and (d) SLA models are shown in these figures.

Figure 5.11: Integral cross sections of the γd → K0Λp and γd → K+Λn reactions over the angular region of 0.9< cos θΛLab ≤1.0 indicated by (a) the Kaon-MAID and (b) SLA models. The rK1Kγ values are displayed in the figure.
5.2. COMPARISON WITH THE THEORETICAL CALCULATIONS

Figure 5.12: Integral cross sections adding the $\gamma d \rightarrow K^0 \Lambda p$ and $\gamma d \rightarrow K^+ \Lambda n$ reactions over the angular region of $0.9 < \cos \theta_{\Lambda}^{\text{Lab}} \leq 1.0$ indicated by the isobar models. The $r_{K_1K\gamma}$ values are displayed in the figure.

Figure 5.13: Total cross sections of the $\gamma d \rightarrow K^0 \Lambda p$ and $\gamma d \rightarrow K^+ \Lambda n$ reactions indicated by (a) the Kaon-MAID and (b) SLA models. The $r_{K_1K\gamma}$ values are displayed in the figure. Ratios between the total cross sections and the integral cross sections for the $\gamma d \rightarrow K^0 \Lambda p$ and $\gamma d \rightarrow K^+ \Lambda n$ reactions indicated by (c) the Kaon-MAID and (d) SLA models.
5.2.2 Comparison of the inclusive $K^0$ measurement with the calculations

The $K^0$ momentum spectra of the present results were compared with the theoretical calculations based on the isobar models. Figure 5.14(a) and (b) show the spectra in the lower and higher energy regions, respectively.

In the lower energy region, the calculations with the Kaon-MAID model predict the smaller cross section than our results. The shapes of the spectra with the Kaon-MAID model make the peaks in the higher momentum region than those of the measured spectra. In the higher energy region, the difference between the present data and the calculations based on the Kaon-MAID model is not great in the absolute values. However, our results in the low momentum ($p_{K^0}^{\text{Lab}} < 0.3$ GeV/c), especially in the angular regions of $0.9 < \cos \theta_{K^0}^{\text{Lab}} \leq 1.0$ and $0.8 < \cos \theta_{K^0}^{\text{Lab}} \leq 0.9$, are larger than the calculations. The influence of the $K^0\Sigma^0$ and $K^0\Sigma^+$ productions with the Kaon-MAID model can be seen in Fig. 5.15. The contribution of the $\Sigma$ productions is very small in the lower energy region due to under the reaction threshold of the elementary process ($E_\gamma \sim 1.05$ GeV). On the other hand, in the higher energy region the $\Sigma$ contributions are not negligible, especially $0.9 < \cos \theta_{K^0}^{\text{Lab}} \leq 1.0$. However, if the $K^0$ production angle is larger, the influence of the $\Sigma$ production becomes small.

The cross section predicted by the SLA model depends greatly on the $r_{K^1K^\gamma}$ value as shown in Fig. 5.14. The $K^0$ momentum spectra with SLA of $r_{K^1K^\gamma} = -1.0$ have the largest cross section in this figure. If the $r_{K^1K^\gamma}$ value of the SLA model is reduced, the cross sections of the $K^0$ production are small up to the value of $r_{K^1K^\gamma} = -2.5$. The $K^0$ spectra with the SLA model of $r_{K^1K^\gamma} = 0.4474$, which is suggested by the Kaon-MAID model, are quite large and hardly account for the present results (no figure). In the lower energy region, the $K^0$ spectra predicted by the SLA model with the $r_{K^1K^\gamma}$ value from $-1.0$ to $-1.5$ agree well with the experimental data in the absolute value. Especially, the $r_{K^1K^\gamma}$ values of an agreement to the spectra of $\cos \theta_{K^0}^{\text{Lab}} = 0.9 - 1.0$ and $0.8 - 0.9$ were $-1.3$ and $-1.2$, respectively. They were determined using the integral values by each spectra. The shapes of the $K^0$ spectra in this region are similar to the experimental results. In the higher energy region, the $K^0$ spectra with SLA of $r_{K^1K^\gamma} = -1.5$ are almost consistent with our results in the regard of not only the absolute but also the shape. In the low momentum region ($p_{K^0}^{\text{Lab}} < 0.4$ GeV/c) of the higher energy region, the present data are larger than the calculations predicted by the SLA model with the $r_{K^1K^\gamma} = -1.5$. Although the SLA model cannot calculate $\Sigma$ photoproductions, there is the influence of the $K^0\Sigma^0$ and $K^0\Sigma^+$ productions in this momentum region. Moreover, in the larger angle regions of $0.7 < \cos \theta_{K^0}^{\text{Lab}} \leq 0.8$ and $0.6 < \cos \theta_{K^0}^{\text{Lab}} \leq 0.7$ the calculations with SLA of $r_{K^1K^\gamma} = -1.5$ predicts the underestimation against our results.
5.2. COMPARISON WITH THE THEORETICAL CALCULATIONS

Figure 5.14: Comparison of the $K^0$ momentum spectra with the theoretical calculation based on the isobar models, Kaon-MAID (black lines) and SLA, in the photon energy regions (a) from 0.90 to 1.00 GeV and (b) from 1.00 to 1.08 GeV. The $r_{K\gamma}$ values in the SLA model are displayed in the figure. The error bars represent the total error of the statistics and systematics.
Figure 5.15: Comparison of the $K^0$ momentum spectra with the theoretical calculations of the $K^0\Lambda$ and $K^0\Sigma^{0,+}$ productions of the Kaon-MAID model in the photon energy regions (a) from 0.90 to 1.00 GeV and (b) from 1.00 to 1.08 GeV. The error bars of the spectra represent the total error of the statistics and systematics.
The comparison of the $K^0$ momentum spectra of the angular region of $0.9 < \cos \theta_{K^0}^{\text{Lab}} \leq 1.0$ in the lower energy region between our results and the calculations with the RPR model is shown in Fig. 5.16. In a similar tendency of the Kaon-MAID model, this model cannot explain the present $K^0$ spectra for not only absolutes value but also shapes. Although the shape of $K^0$ spectra predicted by the RPR model looks like that by the Kaon-MAID model, the difference in the absolute value between our results and the RPR model is larger than that between the results and the Kaon-MAID model. The shaded region in the figure takes the uncertainties of the transition moments of the $D_{13}(1900)$ resonance into account. Nevertheless, the calculations suggesting a missing strength in the elementary cross section cannot explain the shape of the experimental results.

Figure 5.16: Comparison of the $K^0$ momentum spectra with the theoretical calculation based on the RPR model in the photon energy region from 0.90 to 1.00 GeV. and the angular range of $0.9 < \cos \theta_{K^0}^{\text{Lab}} \leq 1.0$. The error bars show the statistics error.
5.2.3 Comparison of the inclusive $\Lambda$ measurement with calculations

The $\Lambda$ momentum spectra of the present results were compared with the calculations adding the $K^0\Lambda$ and the $K^+\Lambda$ processes based on the isobar models. Figure 5.17(a) and (b) show the spectra in the lower and higher energy regions, respectively.

The parameters of the Kaon-MAID model were fitted using the experimental data of the $K^+\Lambda$ reaction from the SAPHIR group [32]. The total cross section of the $\gamma p \rightarrow K^0\Lambda$ reaction provided by SAPHIR [32, 34] is different from that by CLAS [42] (see Fig. 1.2). However, the difference is small in the threshold region ($<1.1$ GeV). The Kaon-MAID model is expected to reproduce the differential cross section for the $\gamma p \rightarrow K^+\Lambda$ channel in this region. In the lower energy region, the $\Lambda$ momentum spectra adding the $K^0\Lambda$ and $K^+\Lambda$ reactions are smaller than the experimental results in the absolute value. In this energy region, the shapes of spectra might not be sensitive to the angular distribution in the c.m. system. On the other hand, the shapes of $\Lambda$ spectra are important in the higher energy region [113] and agrees with the experimental results in this region. However, the $\Sigma^0$ contributions cannot be negligible in this region, especially $0.9 < \cos\theta^\Lambda_{\text{Lab}} \leq 1.0$. The experimental results in the absolute value might be slightly smaller than the calculations based on this model.

As described in Sec. 5.2.1.1, the parameters of the SLA model were obtained by fitting the poorer statistical data [100] than that for the Kaon-MAID model. Although the certainties are not higher than the Kaon-MAID model, the SLA model applied until the photon energy of 1.5 GeV is expected to explain the differential cross section for the $\gamma p \rightarrow K^+\Lambda$ channel. In the lower energy region, the $\Lambda$ spectra with the $r_{K_1K\gamma}$ parameter from $-1.0$ to $-1.5$ agree well with the present data. The $r_{K_1K\gamma}$ values of an agreement to the spectra of $\cos\theta^\Lambda_{K^0} = 0.9$–1.0 and 0.8–0.9 with high statistics were $-1.3$ and $-1.2$, respectively. These $r_{K_1K\gamma}$ values are corresponding to those suggested by the inclusive $K^0$ measurement. In the higher energy region, the $\Lambda$ spectra with the $r_{K_1K\gamma} = -1.5$ are almost consistent with our results. In the larger angle regions of $0.85 < \cos\theta^\Lambda_{\text{Lab}} \leq 0.90$ and $0.80 < \cos\theta^\Lambda_{\text{Lab}} \leq 0.85$ the calculations with SLA of $r_{K_1K\gamma} = -1.5$ predicts the overestimation against our results. This trend is different from the suggestion of the inclusive $K^0$ measurement predicting the underestimation in the larger angle.

Figure 5.18 shows the comparison of the $\Lambda$ integral cross sections between the present results and the calculations based on the isobar models. The vertical lines represent the masses of the nucleon resonances for $S_{11}(1650)$ (line), $P_{11}(1710)$ (dash line) and $P_{13}(1720)$ (dot line). Each mass corresponds to 0.98, 1.09 and 1.10 GeV of the photon energy in the neutron rest frame, respectively. $\dagger$. Our result rises up more quickly from the reaction threshold than the calculation with the Kaon-MAID model. The difference between our result and the calculation is large around the photon energy of 1.0 GeV but becomes smaller in the high energy region. On the other hand, the present result is slightly larger than the calculation predicted by the SLA model with the $r_{K_1K\gamma} = -1.5$ value. As described in Table 2.2, $\Sigma^0$ decays to $\Lambda\gamma$ with the branching ratio of 100%. In the inclusive $\Lambda$ measurement, the $\Lambda$ events cannot be distinguished from the $\Sigma^0$ productions ($K^+\Sigma^0$ and $K^0\Sigma^0$). The $\Sigma^0$ contributions in the framework of the Kaon-MAID model are shown in Fig. 5.19. The $\Sigma^0$ contributions under the photon energy of 1.00 GeV are almost negligible and increase with the photon energy. The contributions from the $\Sigma^0$ productions in the photon energy of 1.05 and 1.10 GeV become about 6 and 13% in this framework.

$\dagger$ the target is assumed to be a nucleon with the mass of 940 MeV/c$^2$. 

\[\dagger\]
5.2. COMPARISON WITH THE THEORETICAL CALCULATIONS

Figure 5.17: Comparison of the Λ momentum spectra with the theoretical calculation adding the $K^0\Lambda$ and the $K^+\Lambda$ reactions based on the isobar models, Kaon-MAID (black lines) and SLA, in the photon energy regions (a) from 0.90 to 1.00 GeV and (b) from 1.00 to 1.08 GeV. The $r_{K\gamma}$ values in the SLA model are displayed in the figure.
Figure 5.18: Comparison of the Λ integral cross section with the theoretical calculations based on the isobar models. The error bars show the only statistical error. The systematical uncertainties were estimated to be 14%.

Figure 5.19: Comparison of the Λ integral cross section with the theoretical calculations of the Λ and the Σ^0 productions predicted by the Kaon-MAID model. The error bars of the present results show the only statistical error. The systematical uncertainties were estimated to be 14%.
5.2.4 Elementary amplitudes of the $\gamma n \rightarrow K^0 \Lambda$ reaction

Figure 5.20 shows the energy dependence of the total cross section on the $\gamma n \rightarrow K^0 \Lambda$ reaction suggested by the Kaon-MAID and SLA models.

In the framework of the Kaon-MAID model $^\dagger$, the total cross section of the $\gamma p \rightarrow K^+ \Lambda$ reaction, which had been experimentally studied and theoretically reproduced, rises up quickly from the reaction threshold than that of the $\gamma n \rightarrow K^0 \Lambda$ reaction (see Fig. 5.13). The excitation function of the $\gamma p \rightarrow K^+ \Lambda$ reaction near the threshold has mainly the contribution of the $S_{11}(1650)$ resonance of the $s$-channel. On the other hand, that of the $\gamma n \rightarrow K^0 \Lambda$ reaction have the slower rising. This difference seems to come from the small transition moment of the $S_{11}(1650)$ resonance ($-0.28$) as mentioned in Sec.5.2.1.2. The experimental results of the cross section, which can be seen in Fig. 5.18, suggested that the excitation function of the $\gamma n \rightarrow K^0 \Lambda$ reaction has the quicker rising from the reaction threshold than that predicted by the Kaon-MAID model. Although the systematic uncertainties of the tagged photon energy were estimated to be $\pm 10$ MeV (see Sec. 3.2.3), the results suggest the quick rising in view of these uncertainties.

As shown in Fig. 5.11, the $K_1(1270)$ resonance of the $t$-channel exchange contributes a lot to the cross section in the framework of the SLA approach. The total cross section of the $\gamma n \rightarrow K^0 \Lambda$ reaction depends on the $r_{K_1K\gamma}$ value which determines the strength of the photo-coupling in the $K^0K^0\gamma$ vertex. The importance of the $K_1(1270)$ exchange is suggested by R. A. Adelseck and L. E. Wright [73] and almost all recent isobar models include the $K_1(1270)$ contribution. Then, the main role of the $K_1(1270)$ exchange in the SLA model is to compensate the neutron contribution [113]. Our results of the total cross section have an agreement with the

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$^\dagger$the elementary amplitudes can be calculated from http://wwwkph.kph.uni-mainz.de/MAID/kaon/.

The results of various conditions are given in Appendix B.
SLA model in the $r_{K^1 K_\gamma}$ value from $-1.0$ to $-1.5$. However, the SLA model, which is applied until the photon energy of 1.5 GeV, predicts that the total cross section on the $\gamma n \rightarrow K^0\Lambda$ reaction increases with the photon energy up to $E_\gamma=1.5$ GeV. There is a larger difference with the Kaon-MAID model with the plateau region from 1.2 GeV. Whether the total cross section of the $\gamma n \rightarrow K^0\Lambda$ reaction becomes the plateau or increase with the photon energy cannot be confirmed from our results. The results of the further photon energy region are sure to help the interpretation on the $\gamma n \rightarrow K^0\Lambda$ reaction.

The angular distributions of the $\gamma n \rightarrow K^0\Lambda$ reaction in the c.m. system are shown in Fig. 5.21. The spectra were suggested by the Kaon-MAID and SLA models for the photon energy of 0.97 (a) and 1.1 GeV (b).

![Angular Distribution of the $\gamma n \rightarrow K^0\Lambda$ Reaction](image)

Figure 5.21: Angular distributions of the $\gamma n \rightarrow K^0\Lambda$ reaction in the c.m. system suggested by the Kaon-MAID and SLA models in the photon energy of (a) 0.97 and (b) 1.10 GeV. The $r_{K_1 K_\gamma}$ values are displayed in the figure.

The prediction of the Kaon-MAID model for the differential cross section of the $\gamma n \rightarrow K^0\Lambda$ reaction make the bump around the angular region $\cos \theta_{K_0}^{\text{Lab}}=0$. In this framework, the transition moments of the both $P_{11}(1710)$ and $D_{13}(1960)$ resonances become small. For the information, the transition moment of the $D_{13}(1960)$ resonance, which is a missing resonance and has not been observed, is predicted by the quark model instead of the helicity amplitude. Therefore, the both resonances have little contribution to the angular distributions of the $\gamma n \rightarrow K^0\Lambda$ process. The contribution of the $S_{11}(1650)$ resonance, which transition moment is $-0.28$, is not so great but cannot be negligible. However, the angular distribution is not too much sensitive to the $S_{11}(1650)$ resonance (see Figs. B.3 and B.4). Therefore, the angular distribution of the $\gamma n \rightarrow K^0\Lambda$ process is mainly formed by the Born term, $K^*(892)$ and $K_1(1270)$ in the $t$-channel, and the $P_{13}(1720)$ resonance in the $s$-channel. The experimental results suggest that the shapes of the $K^0$ momentum spectra in the laboratory system contradict the theoretical calculations based on the Kaon-MAID model. This contradiction seems to cause the angular distribution of the elementary $\gamma n \rightarrow K^0\Lambda$ production in the c.m. system.

As described in Sec. 5.2.1.2, the $r_{K_1 K_\gamma}$ value was determined from the comparison of the fitting in the $K^0\Sigma^+$ and $K^+\Sigma^0$ channels in the Kaon-MAID model. However, the experimental results of the $K^0\Sigma^+$ reaction were pointed out as the insufficiency of the background estimation by the same SAPHIR collaboration [35]. New results of the total cross section for the $\gamma p \rightarrow K^0\Sigma^+$ reaction become 30 to 40% lower than the previous one. Moreover, the other data of this channel from CLAS [114] and CBELSA [38] agree well with the new SAPHIR data. Therefore,
it is not sure that the \( r_{K_1 K \gamma} = -0.447 \), in the Kaon-MAID approach becomes a realistic value. P. Bydžovský et al. also tried to re-fit the \( r_{K_1 K \gamma} \) parameter in the Kaon-MAID model using the previous NKS results (\( \gamma d \to K^0 X \) channel). However, the shape of \( K^0 \) momentum spectra could not be reproduced \[113\].

The angular distribution suggested by the SLA model with the larger \( r_{K_1 K \gamma} \) value than \(-2.5\) becomes the backward peak. If the absolute of the \( r_{K_1 K \gamma} \) value is large, the backward peak is suppressed and the angular distribution is close to be flat. As described above, the main role of the \( K_1(1270) \) exchange is to compensate the neutron contribution of the Born s-channel term. The individual contribution in the neutron exchange is large and makes the remarkable enhancement to the backward hemisphere in this model. Therefore, the increasing absolute of the \( r_{K_1 K \gamma} \) value means the increasing contribution of the \( K_1(1270) \) exchange and then urges to suppress the backward peak of the neutron exchange. The SLA model with the \( r_{K_1 K \gamma} \) value from \(-1.0\) to \(-1.5\) is reproduced in the present results. The angular distributions predicted by the SLA model with this \( r_{K_1 K \gamma} \) region become the backward peak in the threshold region.

Here, the difference of the angular distribution of the Kaon-MAID and SLA model at the photon energy of 1.0 GeV is discussed. The contributions of each term for the \( K^0 \Lambda \) photoproduction In the framework of the Kaon-MAID model are shown in Fig. 5.22 Those in the SLA model with \( r_{K_1 K \gamma} = -1.405 \) are in Fig. 5.23. In each figure, The (a) and (b) in each figure represent the angular distributions from the individual contributions of each term, and the (c) shows those without the given contribution. In the framework of the Kaon-MAID model the angular distribution of the \( \gamma n \to K^0 \Lambda \) process is roughly formed by the Born term, \( K^*(892) \) and \( K_1(1270) \), and the \( P_{13}(1720) \) resonance from the resonance term of s-channel. The SLA model includes these terms and four hyperon resonances. At the first face, the contributions of hyperon resonances differ and it is noted that the \( u \)-channel exchange plays the important role in the backward. However, in the framework of the Kaon-MAID model the \( K^*(892) \) and the \( P_{13}(1720) \) resonances have the large contribution and the contributions of the Born term are strongly suppressed by the hadronic form factor. On the other hand, in the SLA model the \( K_1(1270) \) resonance and the Born term, especially neutron, have the larger contributions than those of the Kaon-MAID model. The different treatment of the Born term is important for the angular distribution of the \( \gamma n \to K^0 \Lambda \) reaction. Because, the individual terms of the Born exchange (\( n, \Lambda \) and \( \Sigma^0 \)), no contribution of kaon exchange in \( K^0 \) productions, make the enhancement to the backward. The elementary amplitudes of the \( K^0 \Lambda \) production in the SLA model is overly complicated but it is a confessed fact that the contribution of the neutron exchange has no small effect for the backward peak. Although whether the backward peak of the \( K^0 \) distribution suggested by the present results comes mainly from the Born term, hyperon resonances or the interference cannot be distinguished, the neutron exchange of the Born term can be one of the candidates making the backward peak. Here, there is a concern for the treatment of the hadronic form factor in the Kaon-MAID model. The hadronic form factor leads to reducing of divergences which are inherent at the high energy to most of isobar models \[69,99\]. The inclusion of the hyperon resonances is proposed for other method to reduce divergence \[65\]. The hadronic form factor is worked out recently by R. M. Davidson and R. Workman \[68,115\] and further used in a combination with hyperon resonances by S. Janssen et al. \[70\]. In these recent investigations, the Kaon-MAID model was suggested the cutoff value of the hadronic form factor was too tight. S. Janssen et al. have introduced the Ghent model with soft hadronic form factors including the same resonances as the Kaon-MAID model and adding two hyperon resonances to avoid tight cutoff.
Figure 5.22: The contribution of each term for the \( K^0\Lambda \) photoproduction in the photon energy of 1.0 GeV in the Kaon-MAID model. (a) and (b) angular distributions of the individual contribution. (b) those without the given contribution.

Figure 5.23: The contribution of each term for the \( K^0\Lambda \) photoproduction in the photon energy of 1.0 GeV in the SLA model with \( r_{K_1K\gamma} = -1.405 \) (a) and (b) angular distributions of the individual contribution. (b) those without the given contribution.
Chapter 6

Conclusion

Investigation of kaon production on the nucleon by the electromagnetic interaction provides invaluable information on the production mechanism, the missing resonances problem and the production mechanism of a quark pair. Especially, kaon photoproduction play an important role in the threshold region, can be described by only four elementary amplitudes In principle, these amplitudes can be experimentally determined “completely” by the measurement of sixteen observables (differential cross section, three single- and twelve double-polarizations). However, the amplitudes of the $\gamma p \rightarrow K^+\Lambda$ reaction with several kinds of observables cannot even be interpreted in spite of the theoretical efforts. To overcome the current situation, the experimental data of various set such as for other isospin channels have been eagerly awaited.

The $\gamma n \rightarrow K^0\Lambda$ reaction among six isospin channels plays an important role in the investigation of the production mechanism due to the following unique features. The $K\Lambda$ (isospin:$I=1/2$) production is simpler than the $K\Sigma$ ($I=3/2$) production because the contributions of $\Delta^*$ ($I=3/2$) resonances are forbidden by the isospin. The elementary amplitudes of the $K^0\Lambda$ reaction are constrained by those of the $K^+\Lambda$ because no charge in the initial and final states are involved and the isospin symmetry are considered.

Based on the success of the previous $K^0$ measurement using a neutral kaon spectrometer (NKS), we had designed and constructed a upgraded new neutral kaon spectrometer (NKS2) at the Laboratory of Nuclear Science, Tohoku University (LNS-Tohoku). NKS2 has an extended acceptance in the forward region compared to that of NKS. NKS2 consists of a dipole magnet, two types of drift chambers, plastic scintillation hodoscopes and electron veto scintillation counters. The photons were generated via bremsstrahlung and were tagged by the STB-tagger system event by event in the photon energy region from 0.8 to 1.1 GeV. The experiment was carried out to investigate the $\gamma n \rightarrow K^0\Lambda$ reaction by detecting $K^0$ and $\Lambda$ from the deuteron in the decay channels of $K^0 \rightarrow \pi^+\pi^-$ and $\Lambda \rightarrow p\pi^-$. The $K^0$ (about 700 events) and $\Lambda$ (about 4000 events) peaks are clearly seen in the $\pi^+\pi^-$ and $p\pi^-$ invariant mass spectra when the vertex points are reconstructed outside the target. The widths of $K^0$ and $\Lambda$ were 5.24±0.34 MeV/$c^2$ and 2.06±0.05 MeV/$c^2$ ($\sigma$) in the energy region of $0.9 < E_\gamma \leq 1.0$ GeV, respectively. The resolution of the $K^0$ invariant mass was improved by a factor of three compared with that of the previous experiment.

(1) The momentum spectra for the inclusive $K^0$ measurement were obtained for the two photon energy regions, $0.90 < E_\gamma \leq 1.00$ GeV (lower) and $1.00 < E_\gamma \leq 1.08$ GeV (higher), with an extensive coverage for the $K^0$ production angle. The $K^0$ momentum spectra in the angular region of $0.9 < \cos \theta^\text{Lab}_K \leq 1.0$ and in the lower energy region were compared with those of the previous experiment. The two results show good agreement within statistical errors. (2)
The momentum spectra for the inclusive Λ measurement were also obtained for the two photon energy regions for the first time. (3) The integral cross sections of the $\gamma d \rightarrow K^0 X$ reaction over the angular region $0.5 < \cos \theta_{K^0}^{\text{Lab}} < 1.0$ in the laboratory system and (4) the total cross sections of the $\gamma d \rightarrow \Lambda X$ reaction were deduced for the first time.

The integral cross sections of the $\gamma d \rightarrow K^0 X$ reaction were compared with the total cross section of the $\gamma p \rightarrow K^+ \Lambda$ reaction from the SAPHIR group. They agree each other in the energy region of $E_\gamma < 1.0$ GeV reasonably well. It suggests that the energy dependence of the $\gamma n \rightarrow K^0 \Lambda$ reaction is almost the same as that of the $\gamma p \rightarrow K^+ \Lambda$ in the threshold region. On the other hand, the angular distributions in the center of mass system (c.m.) show different shapes between the $K^0 \Lambda$ and $K^+ \Lambda$ reactions. The $K^0 \Lambda$ reaction, which is indicated by the global fit of our results, has the larger cross section in the backward while the $K^+ \Lambda$ shows the slightly forward distribution.

The present results were compared with the theoretical calculation based on the elementary amplitudes of isobar models, i.e. Kaon-MAID and SLA, and folding a realistic deuteron wave function. The momentum spectra for the inclusive $K^0$ measurement favor the calculations predicted by the SLA model after adjusting the free parameter so as to reproduce the backward angular distribution. The Λ momentum spectra were also compared with the calculations summing the $K^+ \Lambda$ and $K^0 \Lambda$ reactions. The $r_{K^0 K^+ \gamma}$ values predicted by the $K^0$ measurement are consistent with those by the Λ measurement in the lower energy region. In the higher energy region and forward region, the results from the $K^0$ and Λ measurements show reasonable agreement. Moreover, the calculations predicted by the RPR model were compared with our results in the energy region of $E_\gamma=0.9$–1.0 GeV and in the angular region of $0.9 < \cos \theta_{K^0}^{\text{Lab}} \leq 1.0$. The present results were at least 2 times larger than the calculations.

Our results provide the experimental investigation of the $\gamma n \rightarrow K^0 \Lambda$ reaction with a broader view.
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Appendix A

Recoil polarization

The polarization observables are the sensitive probes for the investigation of hadronic processes. The kaon photoproduction processes are described using the combination of the four amplitudes which are well known as Chew, Goldberger Low and Nambu (CGNL) amplitudes, helicity amplitudes or transversity amplitudes. On the other hand, sixteen observables, which are one differential cross section, three kinds of single observables and twelve kinds of double observables, are defined using these amplitudes [71]. The four amplitudes, which consist of a real and an imaginary parts by each amplitude, can be "completely" determined by the measurements of these observables. The recoil polarization ($P$) among these observables can be obtained from the present data.

The recoil polarization was measured using the angular distribution of protons from the Λ hyperon by the weak decay. This property arises from the interference of the parity violating s-wave state and the parity conserving p-wave state. Here, the recoil polarization for the inclusive Λ measurement on the deuteron can be measured in this experiment. The normal vector to the production plane ($n$) is generally defined as follows,

$$ n = \frac{E_\gamma \times p_K}{|E_\gamma \times p_K|}, $$ (A.1)

where $E_\gamma$ and $p_K$ are the three-vector of the photon energy and the kaon momentum, respectively. However, the kaon momentum cannot be determined in the case of the inclusive Λ measurement. Therefore, the normal vector to the production plane is defined using the Λ momentum ($p_\Lambda$) as follows,

$$ n = -\frac{E_\gamma \times p_\Lambda}{|E_\gamma \times p_\Lambda|}. $$ (A.2)

In this analysis, the Λ recoil polarization ($P_\Lambda$) was obtained directly from the asymmetry of the decay angular distributions as follows,

$$ P_\Lambda = \frac{2 \frac{N_1 - N_2}{\alpha N_1 + N_2}}, $$ (A.3)

where $N_1$ and $N_2$ are the number of events with $\cos \theta > 0$ and $\cos \theta < 0$, which $\theta$ is defined as the angle between the proton from the Λ decay and $n$ in the Λ rest frame. The Λ decay parameter ($\alpha$) indicates the self-analyzing power of the Λ hyperon and have been experimentally determined to be $0.642 \pm 0.013$ [90].
A.0.4.1 Experimental results

The recoil polarization for the inclusive $\Lambda$ measurement on the deuteron are shown in Fig. A.1. The histograms (a,b) and (c,d) represent the results requiring the decay volume selection and without this selection, respectively. The amount of the background was estimated using the fitting results of the invariant mass. In the same way as the differential cross section, the number of $\Lambda$ events was estimated to be the rest number subtracting the background from the number requiring Eq. (3.39). The given error bars in these figure are the statistical error calculated using the standard error and the error propagation.

The closed circles (black) and the closed squares (red) in Fig. A.2 show the recoil polarization with $p_\Lambda \cdot \hat{x} > 0$ (left arm in NKS2) and $p_\Lambda \cdot \hat{x} < 0$ (right arm), respectively. Although the left and right arms in this spectrometer are not strictly symmetry by considering the magnetic field, this asymmetry contribute little to the result of the recoil polarization according to the estimation of the Monte-Carlo simulation. However, the present results depend on the $\Lambda$ direction in the photon energy from 1.00 to 1.08 GeV. It means that the black closed circles in Fig. A.2(b) and (d) show the different tendency of the red closed squares. This tendency between the recoil polarization was denoted by the both results requiring the decay volume selection (b) and without this selection (d). This tendency could not be explained qualitatively and the present results did not have enough confidence. Therefore, the results of the recoil polarization are described in the appendix.

In the side bands of the $p\pi^-$ invariant mass, the $P$ values of Eq. (A.3) requiring the decay volume selection and without this selection were 0 at the 88% and 99% level of confidence, respectively. The $P$ values of the $p\pi^+$ events vanished at the 99% level of confidence. The cause of the good confidence level is that the statistical error was estimated using the standard error instead of the binomial error.

![Figure A.1](image_url)

Figure A.1: Recoil polarization for the inclusive $\Lambda$ measurement on the deuteron requiring the decay volume selection (a,b) and without the decay volume selection (c,d). The given error bars are the statistical error calculated using the standard errors and the error propagation.
**A.0.4.2 Comparison with the previous experiment**

The inclusive Λ events on the deuteron target in the threshold region come mainly from the $\gamma d \rightarrow K^+ \Lambda n$ and the $\gamma d \rightarrow K^0 \Lambda p$ processes. The recoil polarization of this experiment for the inclusive Λ measurement, of course, is made of the contribution of the $K^+ \Lambda$ and the $K^0 \Lambda$ processes.

The recoil polarization observables of the $\gamma p \rightarrow K^+ \Lambda$ reaction on the proton target provided by SAPHIR [34] CLAS [41] and GRAAL [61] were existing for high quality. In the threshold region, the agreement between all experiments is very satisfactory over the full angular range. Figure A.3(b) shows the recoil polarization in the photon energy region from 0.90 to 1.10 GeV by SAPHIR group. This result depending on the angular distribution in the center of mass system should be transferred to that of the momentum dependence in the laboratory system shown in Fig. A.3(c). Then, the photon energies were assumed to be 1.05 (green circles) and 1.10 GeV (blue squares) in the laboratory system and the proton was assumed to be at rest in this transform. The errors applied the errors of the original bins. As the reference, the correlation of the angular distributions in the center of mass system and the momentum of the laboratory system is represented (a).

The recoil polarization by SAPHIR group should be compared with this experimental results in the photon energy region from 1.00 to 1.08 GeV, because the Λ cross section is larger than that in the low photon energy region. This present results of the recoil polarization becomes about $-0.2$ in the momentum region of 0.4-0.6 GeV/c and vanishes in the momentum region of 0.6-0.8 and 0.8-1.0 GeV/c. On the other hand, the recoil polarization of SAPHIR shown in Fig. A.3(c) becomes about $-0.2$ in the low momentum region and is reversed to a little positive over the momentum of 0.8 GeV/c. These two results by SAPHIR and present NKS2 are the
APPENDIX A. RECOIL POLARIZATION

Figure A.3: (c) Recoil polarization observables of the $\gamma p \rightarrow K^+\Lambda$ reaction by SAPHIR group in the energy region from 0.90 to 1.10 GeV [116]. The observables were represented as the angular distribution in the center of mass system. (b) Transferred recoil polarization observables to the momentum dependence in the laboratory system. The photon energies were assumed to be 1.05 (green circles) and 1.10 GeV (blue squares) in the laboratory system and the proton is assumed to be at rest.

similar distributions. The distributions of the recoil polarization from the $K^0\Lambda$ reaction might be similar as that of the $K^+\Lambda$ reaction, because the inclusive $\Lambda$ events on the deuteron are adding the $K^+\Lambda$ and the $K^0\Lambda$ processes.

A.0.4.3 Comparison with theoretical calculations

In this section, the present results of the recoil polarization on the deuteron target are compared with the theoretical calculation using the isobar models, Kaon-MAID model and SLA model. These isobar models are explained in Sec. 5.2.1. This calculations were performed assuming off-shell approximation and zero momentum on the target. The photon energy is taken slightly to be smaller due to the deuteron binding energy (2.225 MeV). Figure A.4(a) and (b) shows the recoil polarization of from the $K^0\Lambda$ process and the $K^+\Lambda$ process by the theoretical calculation, respectively. In the case of $K^0\Lambda$ process on SLA model, the ratio $r_{K^1K^7}$ was taken account as $-1.0$, $-2.0$ and $-3.0$.

The recoil polarization of the $K^0\Lambda$ process suggested by Kaon-MAID model predicts the negative value the until the photon energy of 1.0 GeV and in the photon energy of 1.1 GeV is reversed to be positive in the high momentum region
indicates the negative value. The higher the photon energy is, the larger the absolute of the polarization becomes.

The recoil polarization of the $K^0\Lambda$ process suggested by SLA model becomes the positive value in the photon energy of 1.0 and 1.1 GeV. This results by SLA model are quite a contrast to the suggestions of Kaon-MAID model with the positive values. The cross sections of inclusive $K^0$ and the inclusive $\Lambda$ measurements suggest the good agreement of SLA model with $r_{K, K\gamma}$ parameter from $-1.0$ to $-1.5$. SLA model in this $r_{K, K\gamma}$ region predicts the recoil polarization of the $K^0\Lambda$ process become the large positive value in the photon energy of 1.1 GeV. The recoil polarization of the $K^+\Lambda$ process indicates the negative value.

![Figure A.4: Recoil polarization indicated by the theoretical calculations for (a) the $\gamma d \rightarrow K^0\Lambda p$ reaction and (b) the $\gamma d \rightarrow K^+\Lambda n$ reaction.](image)

As previously described, the inclusive $\Lambda$ events on the deuteron target near the threshold come mainly from the $\gamma d \rightarrow K^+\Lambda n$ and the $\gamma d \rightarrow K^0\Lambda p$ processes. In addition, the weights of the differential cross sections for each process have to be considered for the comparison with the calculations. On the other hand, the cross sections of the $K^0\Lambda$ and the $K^+\Lambda$ processes near the production threshold is not so different according to the estimation of the present analysis. Moreover, the higher the photon energy is, the larger cross sections become for the threshold region. In the low energy region, the inclusive $\Lambda$ recoil polarization of the experimental results predicts to be not so large value. The theoretical calculations assuming both models suggest to be less than 0.3 in the absolute value for the recoil polarization of the $K^0\Lambda$ and the $K^+\Lambda$ processes. The experimental results cannot persist for the disagreement with both models. On the other hand, this experimental result of the high energy region becomes about $-0.2$ in the momentum region of 0.4-0.6 GeV/c and vanishes in the momentum region of 0.6-0.8 and
0.8-1.0 GeV/$c$. The theoretical calculations assuming Kaon-MAID model predicts to be about $-0.2$, $-0.1$ and $0.0$ in the momentum region of $0.4-0.6$, $0.6-0.8$ and $0.8-1.0$ GeV/$c$ for the recoil polarization adding the $K^0\Lambda$ and the $K^+\Lambda$ processes in the photon energy of 1.1 GeV. This calculations is almost consistent with the experimental results. In SLA model of the $r_{K_iK^\gamma}$ region from $-1.0$ to $-1.5$, the recoil polarization of the $K^0\Lambda$ process become the large positive value in the photon energy of 1.1 GeV. Therefore, the theoretical calculations assuming SLA model for the recoil polarization adding the $K^0\Lambda$ and the $K^+\Lambda$ processes predict to be large positive value at least in the momentum region of $0.4-0.6$ GeV/$c$ in the photon energy region of 1.1 GeV. This theoretical calculations might not be corresponding to the experimental results.

The recoil polarization of $K\Lambda$ process receives the large contribution from the interference between kaon resonances in the $t$-channel and nucleon resonances in the $s$-channel. At least in the framework of Kaon-MAID model, the sign of the recoil polarization is sensitive for the sign of coupling constants of $K^*(892)$ and nucleon resonances. Thus, the recoil polarization plays an important role for the investigation of the nucleon resonances. Unfortunately, it is not possible enough to discuss from the present results. This will require the separation of the $K^+\Lambda$ and the $K^0\Lambda$ processes. Moreover, the data taking in the reverse of the magnetic field will be preferred.
Appendix B

Kaon-MAID model

The elementary cross sections of Kaon-MAID model can be calculated from a web-page. Here, the results of various conditions represent in order to interpret the contributions of each resonance.

The total cross sections without each resonance are shown in Fig. B.1. Moreover, the total cross sections with opposite signs of coupling constants against the original Kaon-MAID model for each resonance are shown in Fig. B.2.

Figure B.1: Total cross sections for (a) the $\gamma n \rightarrow K^0 \Lambda$ reaction and (b) the $\gamma p \rightarrow K^+ \Lambda$ reaction without each resonance.

Figure B.2: Total cross sections for (a) the $\gamma n \rightarrow K^0 \Lambda$ reaction and (b) the $\gamma p \rightarrow K^+ \Lambda$ reaction with opposite signs of coupling constants against the original Kaon-MAID model for each resonance to guess the contribution of the interference.
The angular distributions without each resonance are shown in Fig. B.3. Moreover, the angular distributions with opposite signs of coupling constants against original Kaon-MAID model for each resonance are shown in Fig. B.4.

Figure B.3: Angular distributions for (a) the $\gamma n \to K^0\Lambda$ reaction and (b) the $\gamma p \to K^+\Lambda$ reaction without each resonance.

Figure B.4: Angular distributions for (a) the $\gamma n \to K^0\Lambda$ reaction and (b) the $\gamma p \to K^+\Lambda$ reaction with opposite signs of coupling constants against original Kaon-MAID model for each resonance to guess the contribution of the interference.
Appendix C

Position tuning of drift chambers

SDC is a position detector installed into the inner of CDC and plays an important role as the improvement of not only the momentum resolution but also the vertex resolution. SDC was designed and built to be mechanically fixed to CDC. However, when SDC was fixed to CDC, the wires of SDC were broken for weakness of the structure of SDC. Therefore, SDC was jointed temporally and could not be fixed mechanically in this experiment. In addition, the relative position between SDC and CDC could not be measured because of the inability to access to SDC after the installation. Therefore, the relative position between SDC and CDC was tuned using the experimental data.

Firstly, the tracking is performed using only CDC. Secondly, the distance between the trajectory and the drift length of SDC is calculated. The relative position between SDC and CDC is tuned using the $\Delta z$- and $\Delta x$-component of this distance ($\Delta z, \Delta x$) which is shown in Fig. C.1. The $\Delta z$ and $\Delta x$ distributions before the tuning depend largely on $\phi_{zx}$ as shown in right figures of Fig. C.2. The sensitive regions to $\Delta z$ and $\Delta x$, which are represented in hatching regions of the two contour figures, are determined to be $|\sin\phi_{zx}| > 0.9$ and $|\cos\phi_{zx}| > 0.9$, respectively. The two right upper figures are one projected of these hatching regions. The relative position of SDC is tuned in parallel to the $zx$-plane as these peaks to be zero. The right lower figure represents $\Delta z$ distributions of green and red regions in the left upper figure. The rotational tune in the $zx$-plane is performed so that two $\Delta z$ distributions overlap. The distributions after tuning was shown in Fig. C.3. In the present analysis, the $y$-component of the relative position is not tuned due to the limitation of the detector resolution. However, it do not have a large influence on the results because the particles through OH are not distributed widely in SDC.

Figure C.1: Definition of $\Delta z$ and $\Delta x$ for the position tune between CDC and SDC
Figure C.2: Distributions of $\Delta z$ (a) and $\Delta x$ (b) before tuning in layer3. The left figures represents the $\phi_{zx}$ dependence. The two right upper figures are one projected of hatching regions. The right lower figure are $\Delta z$ distributions of green and red hatching regions for the rotational tune.

Figure C.3: Distributions of $\Delta z$ and $\Delta x$ after tuning in layer3. The left figures represents the $\phi_{zx}$ dependence. The two right upper figures are one projected of hatching regions. The right lower figure are $\Delta z$ distributions of green and red hatching regions for the rotational tune.
After the relative position between SDC and CDC is tuned, the rotational position of the drift chambers against the photon beam is tuned. Therefore, the $z$-direction of drift chambers is aligned to the direction of the photon beam. The conversion events of photons are used to perform this tuning. The $e^+e^-$ events is represented approximately as follows,

$$E_\gamma \simeq p_{e^+} + p_{e^-}$$  \hspace{1cm} (C.1)  \\
$$= p_{e^+e^-}$$  \hspace{1cm} (C.2)

where $E_\gamma$, $p_{e^+}$ and $p_{e^-}$ are the energy of photon, the momentum of $e^+$ and $e^-$, respectively. Moreover, $p_{e^+e^-}$ is the combined momentum of $e^+$ and $e^-$. The direction of the ongoing photon is defined in the $zx$-plane

$$\sin \theta_{zx} = \frac{p_{e^+e^-} \cdot \hat{x}}{\sqrt{(p_{e^+e^-} \cdot \hat{z})^2 + (p_{e^+e^-} \cdot \hat{x})^2}}$$  \hspace{1cm} (C.3)

where $\theta_{zx}$ means the angle between the combined momentum of $e^+$ and $e^-$ in the $zx$-plane and the $z$-direction in the drift chambers.

Figure C.4 shows the angular distribution before and after tuning. Although the peak position represented as $\sin \theta_{zx}$ have the shift before the rotational tuning, the mean value of the peak becomes zero after the tuning.

![Angular distribution](image)

Figure C.4: Angular distribution between the carbonated momentum of $e^+$ and $e^-$ and the $z$-direction in the drift chambers. The upper figure shows the angular distribution before tuning and the lower shows that after tuning.
Appendix D

Tagged photon energy determined by BM4 STB tagging system

As described in Sec. 3.2.3, the calibrated values of the photon energy by the hadronic productions (HP) were adopted in the present analysis for the photon energy.

Here, the differences of the calibrated energy between using the photon conversion via Sweep Magnet (SM) in 2002 and the various methods represent Fig. D.1. The energy deposit of the lead glass counter is determined by the pedestal of ADC and the gain of the segment number \( i = 17 \) to 0.974 GeV.

Figure D.1: Energy calibration of tagger by various methods. The upper figures are same as Fig. 3.13. The lower left and the lower right figures represent these by the lead glass counter and by the photon conversion via 680 Cyclotron Magnet.
The photon energies using two kinds of the calibrations and the design values are summarized in Table D.1.

Table D.1: Tagged photon energy determined by BM4 STB tagging system

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<th>Segment</th>
<th>Design value using SM</th>
<th>Calibrated value using HP</th>
<th>Segment</th>
<th>Design value using HP</th>
<th>Calibrated value</th>
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Appendix E

Fermi momentum of the nucleon in the deuteron

The momentum distribution of the nucleon in the deuteron are expressed by the Hulthén wave function for the calculation. This wave function is a reasonably good representation of a realistic wave function as follows,

\[ P(p) \propto \frac{p^2}{(p^2 + \alpha^2)^2(p^2 + \beta^2)^2} \quad (E.1) \]

where \( P \) and \( p \) are the probability density and the momentum of the nucleon, respectively. And \( \alpha \) and \( \beta \) are the fitting parameter. When the experimental data for the electron scattering of the deuteron [117] was fitted by Eq. E.1, the values of \( \alpha \) and \( \beta \) are 45.6 MeV/c and 234 MeV/c, respectively. Figure E.1 represents the fitting result and these values was used to determinate the momentum distribution of the nucleon in the deuteron.

![Momentum distribution of the nucleon](image)

**Figure E.1:** Fermi momentum of the nucleon in the deuteron. The experimental data is the momentum distribution from the measurement of the \( d(e, e'p) \) reaction [117]. The line is the Hulthén wave function determined the parameters by the fitting.
Appendix F

Correlations among the frames

The correlations between the laboratory frame and the center of mass frame for \( \gamma n \rightarrow K^0 \Lambda \) reaction are represented for the reference in Fig. F.1. The photon energy with 0.95, 1.00, 1.05 and 1.10 GeV in the laboratory frame react to the rest neutron in this calculation.

Figure F.1: Correlation between the laboratory frame and the center of mass frame for \( \gamma n \rightarrow K^0 \Lambda \) reaction. The upper figures show the correlation for \( K^0 \) and the lower ones present the correlation for \( \Lambda \). The right figures display the correlation with the momentum in the laboratory frame. Also, the left ones are the correlation with the angular distribution in the laboratory frame.


