Photoproduction of neutral kaons on the deuteron near the threshold

February 13, 2005
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Chapter 1

Introduction

1.1 Strangeness production by electromagnetic interaction

The electro-magnetic production of strangeness have been studied both experimentally[1] and theoretically[2] since the 1950s. It was hoped that the reaction should play an important role for the investigation of meson-hadron interaction etc.

However, due to the lack of facilities with high quality photon/electron beam, the study of strangeness production made little progress before 1980’s compared with that of pion production. In recent years, accelerator facilities providing 1 GeV photon/electron beams and equipped the latest detector systems, have been constructed(Table 1.1) and are in operation. With these beams and detector systems, new experimental data of strangeness production by electromagnetic interaction are obtained and give precise information to theoretical investigation.

The search for, namely, missing resonances is one of the subjects in the investigation of photo- and electro-production of strangeness. These resonances have been predicted by QCD models that contain three constituent valence quarks but not validated experimentally in the hadronic reaction such a πN. A reasonable explanation of this is that these resonances are coupled except to πN, such as a KΛ channel. For example, in the $\gamma N \rightarrow K\Lambda$ reaction, new experimental data shows the bump structure around 1.5 GeV in the energy dependence of total cross section[3], and Mart et al. implies that the bump structure is explained by introducing a $D_{13}(1900)[4]$ which is one of the missing resonances. It is believed that strangeness can be a good probe to find unexplored resonances states.

Figure 1.1 shows energy dependence of total cross section of photoproduction for each channels in the threshold region. Although examples of a recent theoretical calculation are shown for all the six channels, high quality experimental data are available only for the two $K^+$ channels, that is, $\gamma p \rightarrow K^+\Lambda$ and $\gamma p \rightarrow K^+\Sigma^0$, and some data for $\gamma p \rightarrow K^0\Sigma^+$. No data have been measured for the other three channels on a neutron, that is, $\gamma n \rightarrow K^0\Lambda, \gamma n \rightarrow K^0\Sigma^0$ and $\gamma n \rightarrow K^+\Sigma^-$. It is because of the experimental difficulty to measure neutral kaons and to prepare pure neutron target.
Figure 1.1: Energy dependence of total cross sections of each channel.

Table 1.1: Electron (photon) beam facilities.

<table>
<thead>
<tr>
<th>accelerator/detector (country)</th>
<th>beam</th>
<th>energy (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELSA[16]/SAPHIR[17] (Germany)</td>
<td>γ</td>
<td>~ 2.6</td>
</tr>
<tr>
<td>JLab/CLAS[18] (U.S.A)</td>
<td>γ, e</td>
<td>0.5 ~ 6.0</td>
</tr>
<tr>
<td>JLab/HMS,SOS (U.S.A)</td>
<td>γ, e</td>
<td>0.5 ~ 6.0</td>
</tr>
<tr>
<td>SPring-8/LEPS[19] (Japan)</td>
<td>ɣ</td>
<td>1.5 ~ 2.4</td>
</tr>
</tbody>
</table>

yet ... TAPS@ELSA,CrystalBall&TAPS@MAMI,Lagrange@GRAAL

1.2 Historical background

1.2.1 Experimental investigation

The first generation of the investigations of strangeness photo-production were carried out until the late 1950s. The data measured for the $\gamma p \rightarrow K^+ \Lambda$ reaction from threshold up to 1.4 GeV contained the differential cross section [5, 6, 7, 8, 9, 10], total cross section[11], final state $\Lambda$ polarization[7, 9] and polarized target[12]. In addition, the measurements with higher energy[13] and those of electro-production[14, 15] were executed. However, theoretical analysis was not improved because only $K^+$ differential cross section on a proton target were achieved precisely in low photon energy region. Precise measurements at high energy, those of polarization and those of other strangeness production channels were still to be conducted at that time.

Several accelerator facilities which provide GeV photon/electron beams started operating, simultaneously, new detector systems arranged for the high statistical strangeness photo-/electro-production data taking became available(Table.1.1) in 1990’s.

New and high quality experimental data are now being provided from SAPHIR,
CLAS and SPring-8.

First, ELSA/SAPHIR group provided high quality new data of the cross sections and polarizations for both $\gamma p \rightarrow K^+\Lambda$ and $\gamma p \rightarrow K^0\Sigma^+$ processes with quality much better than any experiments in the past. A bump structure around $E_\gamma = 1.5$ GeV was clearly indicated in the excitation spectrum [for the first time][3]. The structure was interpreted as a evidence for a missing resonance, $D_{13}[4]$. In this experiment, although cross section and polarization of $\gamma p \rightarrow K^0\Sigma^+$ process were measured[20], statistics was much poor than the that of $K^+$ production process. Recently, they reported more precise result based on data acquired late[21]. It was claimed that strangeness production by electromagnetic interaction served as a powerful probe for the investigation of hadron physics.

JLab/CLAS group measured transferred polarizations in the exclusive $\bar{e}p \rightarrow e'K^+\bar{\Lambda}$ reaction for the first time[22]. The polarizations are sensitive to the resonance contributions in theoretical calculations, and no model can explain the results. The group also measured $\gamma p \rightarrow K^+\Lambda$ process[23]. Although the same bump structure as observed in SAPHIR data was shown in the energy dependence of cross section, absolute value is different with SAPHIR data at forward angle. This discrepancy results in different parameter sets in the isobar models, and has been a puzzle to be resolved.

### 1.2.2 Theoretical investigation

Strangeness production by electromagnetic interaction has been theoretically analyzed with isobar models since early year[2]. In the threshold region, the isobaric models[24, 25, 26, 27, 28, 29, 30] are interested and important although various theoretical approaches were attempted. Some of other theoretical approaches, e.g. Regge pole methods and parton-quark approaches, concern higher energy domains. In this paper, we take notice of the isobar models.

To be continued.....

### 1.3 Purpose of present study

The $\gamma n \rightarrow K^0\Lambda$ has unique features in the investigation of strangeness production process by electromagnetic interaction as follows,

1. All particles relating this reaction have no charge. In t-channel, because K-meson of intermediate state couples to photon by electromagnetic interaction which naively relates electric charge or magnetic moment of K-meson, Born term does not contribute to this reaction.

2. The sign of coupling constant $g_{KNS}$ in u-channel is opposite to that of $\gamma p \rightarrow K^+\Lambda$ reaction from the isospin symmetry.

Due to these features, the interferences among diagrams are different from the $K^+\Lambda$ production process. Furthermore, the contributions of nucleon resonances are expected
to be small by measuring this reaction in the threshold region. Therefore, the measurement of this process and comparison with the $K^+$ production data in the threshold region allow us to investigate the reaction mechanism by unraveling the various contributions from each diagrams.

The cross sections for elementary process of $\gamma p \to K^+\Lambda$ and $\gamma n \to K^0\Lambda$ as function of the photon energy and angular dependences are calculated using the program developed by Sotona and Bydžovský[31].

The results are shown in Fig.1.2. For $\gamma p \to K^+\Lambda$ process, both photon energy and angular dependence calculated by two models agree with each other because the parameters of the models are derived by fitting the experimental data of $K^+$ production. However, for $\gamma n \to K^0\Lambda$ process, both dependence are quite different model by model. This indicate that the $K^0$ production process may provide additional information on the strangeness production which can not obtained from the $K^+$ production process.

By the way, it is noticed that the SLA model is originally applicable only for $K^+\Lambda$ channel. Therefore, when it is applied to $K^0\Lambda$ channel, this model has a free parameter, $r_{K\bar{K}}$ which is relevant to the decay width of K1 resonance. In the calculation by SLA model shown in Fig.1.2, the value for $g_{K^0\Lambda\gamma}$ was taken from that of Kaon-MAID, which was derived from the experimental data of $\gamma p \to K^0\Sigma^+$ process.

We had already measured $K^0$ quasi-free production on a carbon target and established the method of experiment and analysis. In the framework of quasi-free process, our experimental data was compared with the theoretical calculations[32]. The purpose of this experiment is investigation of the strangeness elementary production using a deuteron target in the threshold region.

Figure 1.2:
Chapter 2
Experimental

In this chapter, experimental method and apparatus are described. The basic idea to measure $K^0$s is discussed in Sect.2.1.

In this experiment, $K^0$s were measured in $\pi^+\pi^-$ decay channel by Neutral Kaon Spectrometer (NKS) which was developed in the Laboratory of Nuclear Science of Tohoku University (LNS-Tohoku). The detectors system is described in Sect.2.3. This experiment was carried out using 1 GeV photon beam at the second experimental hall in LNS-Tohoku. The photon beam is generated via bremsstrahlung and tagged by STB-tagger system, which is explained in Sect.2.2.

In order to investigate $K^0$ elementary production process, the liquid deuterium target was used. The target system was developed for this experiment and provided the stable liquid state deuterium during experimental period as described in Sect.2.4.

Online trigger condition and data acquisition system are explained in Sect.2.5. In Sect.2.6, data sets obtained in the present study are summarized.

2.1 Method

We measured $\gamma n \to K^0\Lambda$ process on a deuteron. Because both $K^0$ and $\bar{K}^0$ have same decay modes, generated $K^0$ can change to $\bar{K}^0$, e.g. via $2\pi$ or $3\pi$ as intermediate state.

$$K^0 \leftrightarrow \left\{ \frac{2\pi}{3\pi} \right\} \leftrightarrow \bar{K}^0$$

In the view of quark diagram, $K^0$ and $\bar{K}^0$ are mixed via namely box diagram,
Although $K^0$ and $\bar{K}^0$ are not eigenstate of CP conversion, final states of $2\pi$ and $3\pi$ are CP eigenstates,

$$CP|\pi\pi> = +1 \cdot |\pi\pi>$$
$$CP|\pi\pi\pi> = -1 \cdot |\pi\pi\pi>$$

In the assumption that CP conversion is conservation in weak interaction, initial state of decay should be also eigenstate of CP. Such states are made of linear combination of $K^0$ and $\bar{K}^0$ as follows,

$$|K^0_S> = \frac{1}{\sqrt{2}}\{ |K^0> - |\bar{K}^0> \}, \quad CP|K^0_S> = +1 \cdot |K^0_S>$$
$$|K^0_L> = \frac{1}{\sqrt{2}}\{ |K^0> + |\bar{K}^0> \}, \quad CP|K^0_L> = -1 \cdot |K^0_L>,$$

where the phase of $|K^0>$ is chosen so that $C|K^0> = +1 \cdot |K^0>$.

When $K^0$ is generated, its state is also described as linear combination of $K^0_S$ and $K^0_L$. Therefore, the probability of measuring $K^0$ as $K^0_S$ is 50 %. The life time of $K^0_L$ which decay into 3 pions is longer than that of $K^0_S$ because the phase space of 3 pions is smaller than that of 2 pions. Table 2.1 shows the properties of both $K^0_S$ and $K^0_L$.

We detected the $K^0$ via the $K^0_S \rightarrow \pi^+\pi^-$ decay channel.

<table>
<thead>
<tr>
<th>Table 2.1: Property of $K^0$.</th>
</tr>
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<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>$K^0_S$</td>
</tr>
<tr>
<td>mass</td>
</tr>
<tr>
<td>$c\tau$</td>
</tr>
<tr>
<td>main decay mode</td>
</tr>
<tr>
<td>$\pi^+\pi^-$ (68.6 %)</td>
</tr>
<tr>
<td>$2\pi^0$ (31.4 %)</td>
</tr>
<tr>
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</table>

2.2 Tagged photon beam at Laboratory of Nuclear Science (LNS)

LNS is one of a few laboratories providing the photon beam with energy of around 1 GeV. Figure 2.1 shows the schematic view of the experimental hall. The 200 MeV electron beam from LINAC is injected to 1.2 GeV STrecher Booster (STB) ring and boosted up to 1.2 GeV, and kept for 20 sec in the ring.

The photon is generated via bremsstrahlung and an scattered electron is tagged by STB-Tagger. Figure 2.2 shows the schematic view of STB-Tagger.

The STB-Tagger is an internal tagging system and located at one bending corner, which consists of 11$\mu$m$\phi$ carbon string radiator, an analyzing magnet, 50 segments of finger plastic scintillators (TagF) and 12 segments of backup counter (TagB).
Because tagger counters are located nearly circulating electron beam, large backgrounds exist. The trajectory of these background is not same with scattered electron from radiator, therefore the coincidence between TagF and TagB is required. One backup counter corresponds to 4 finger counters in coincidence logic.

The STB-Tagger is constructed to serve uniform intensity photon beam tagged from 0.8 to 1.1 GeV by moving radial position of the radiator.

In order to keep photon intensity uniform, the radiator is moved according to the remaining current of circulated electron beam. When the radiator move, the arrival points of scattered electrons at tagger also shift. Therefore, the drift length of radiator is limited so that the shift of arrival points of scattered electrons are less than the half width of a tagger counter.

Figure 2.3 shows the beam cycle. The beam intensity was adjusted about 2~3 mA so that summation of the counting rate of tagger counters was about 2~3 MHz. From the limit of drift length of radiator and the

The energy calibration was carried out before, and so the correlation between a segment of TagF and photon energy was estimated.

Number of tagged photons are counted by scaler in each segment of TagF. The method to estimate the number photon bombarded on target is described in Sect. 3.9.2.
2.3 Neutral Kaon Spectrometer (NKS)

K⁰’s were measured with NKS by detecting $K_0^0 \rightarrow \pi^+\pi^-$ decay channel. NKS was used as a TAGX spectrometer at the Electron synchrotron of Institute of Nuclear Study, University of Tokyo (INS-ES)[33] and moved to Tohoku University after the shutdown of INS-ES. Figure 2.5 shows the detector configuration. The target cell was located in the vacuum chamber at the center of spectrometer. Inner hodoscope(IH) surrounded the vacuum chamber and acted as a time 0 counter. Two types of drift chambers, straw drift chamber(SDC) and cylindrical drift chamber(CDC), were located in the magnetic field region for track and momentum analysis. Outer hodoscope(OH) was outside of drift chamber and gave not only the information on time of flight but also the vertical positions of the charged particles. These detectors covered the geometrical acceptance of $\pi \text{ sr}$. K⁰’s were identified by measuring $\pi^+$ and $\pi^-$ in coincidence by left and right detector arms.

Because the $\gamma \rightarrow e^+e^-$ process caused huge backgrounds in trigger level, electron veto counters were set on the middle of OH to reject the charged particles flying on the
2.3. NEUTRAL KAON SPECTROMETER (NKS)

horizontal plane along beam line.

Figure 2.4: Schematic view of NKS.

2.3.1 TAGX Magnet

TAGX magnet was a dipole type magnet with 107 cm diameter and 60 cm gap. The magnetic field was 0.5 Tesla at the maximum with 500 A.

The magnetic field distribution was calculated by TOSCA program. Figure.2.6 shows the distribution of vertical component of the magnetic field along beam line. The strength of magnetic field by TOSCA has about 2% systematic error by comparison with measured values at INS-ES and at LNS.

2.3.2 drift chamber

The tracking device of NKS consisted of two types of drift chambers, namely honeycomb type cylindrical drift chambers and straw type cylindrical drift chambers.

Figure.2.7 shows the structure of these drift chambers. Operation condition is listed in Table.2.2. Due to existence of non uniform electric field, the relation between drift length and drift time (X-T relation) is not linear. The parameters of X-T relation are
adjusted for each layer units. The correct parameters are calculated by iteration of tracking and fitting parameter (see Sect.3.4).

**SDC**

SDC was also a set of two chamber, which covered the angular ranges from 10 to 170 degrees and the radial ranges from 7.18 to 10.19 cm. The sense wires were made of gold plated tungsten(Ø20μm), and the straws were made of aluminized mylar film with 180 μm thickness.

SDC included 4 layers of sense wires.
Figure 2.7:

**CDC**

CDC was a set of two honeycomb type drift chambers, which covered the angular ranges from 15 to 165 degrees, and the radial ranges of 13.8 to 48.6 cm.

The geometrical parameters are listed in Table 2.3. The field wires were arranged hexagonally around sense wire (Fig.2.7). Total 12 layers of the sense wires were grouped into 4, and each group has 3 layers. In the present experiment, the 3rd layers of each group were not used. The sense wires were made of gold plated tungsten ($\phi 30\mu m$) for inner two layers and stainless steel for 3rd layer in each group. The field wires were made of molybdenum ($\phi 100\mu m$).

The inner and outer windows were made of mylar sheet of 200 $\mu m$ thickness.

After this, we define the consecutive numbers from 1 to 16 as the layer number.

<table>
<thead>
<tr>
<th>Table 2.2: Operation condition of drift chamber.</th>
</tr>
</thead>
<tbody>
<tr>
<td>gas mixture</td>
</tr>
<tr>
<td>high voltage</td>
</tr>
<tr>
<td>hit information</td>
</tr>
</tbody>
</table>
Table 2.3: The design of SDC and CDC. Cell size is written in cm or degree [square brackets].

<table>
<thead>
<tr>
<th>Layer No.</th>
<th>straw size (cm)</th>
<th>radius of layers (cm)</th>
<th>#wires (sense)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.475</td>
<td>7.18</td>
<td>19</td>
</tr>
<tr>
<td>2</td>
<td>0.535</td>
<td>8.07</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>0.600</td>
<td>9.07</td>
<td>19</td>
</tr>
<tr>
<td>4</td>
<td>0.675</td>
<td>10.19</td>
<td>20</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Layer No.</th>
<th>cell size (cm)</th>
<th>radius of layers (cm)</th>
<th>#wires (sense)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1.084 [9.0°]</td>
<td>13.8</td>
<td>16</td>
</tr>
<tr>
<td>6</td>
<td>1.249 [9.0°]</td>
<td>15.9</td>
<td>17</td>
</tr>
<tr>
<td>7</td>
<td>1.414 [9.0°]</td>
<td>18.0</td>
<td>16</td>
</tr>
<tr>
<td>8</td>
<td>1.164 [5.4°]</td>
<td>24.7</td>
<td>28</td>
</tr>
<tr>
<td>9</td>
<td>1.263 [5.4°]</td>
<td>26.8</td>
<td>29</td>
</tr>
<tr>
<td>10</td>
<td>1.362 [5.4°]</td>
<td>28.9</td>
<td>28</td>
</tr>
<tr>
<td>11</td>
<td>1.243 [4.0°]</td>
<td>35.6</td>
<td>40</td>
</tr>
<tr>
<td>12</td>
<td>1.316 [4.0°]</td>
<td>37.7</td>
<td>39</td>
</tr>
<tr>
<td>13</td>
<td>1.389 [4.0°]</td>
<td>39.8</td>
<td>40</td>
</tr>
<tr>
<td>14</td>
<td>1.299 [3.2°]</td>
<td>46.5</td>
<td>50</td>
</tr>
<tr>
<td>15</td>
<td>1.357 [3.2°]</td>
<td>48.6</td>
<td>49</td>
</tr>
<tr>
<td>16</td>
<td>1.416 [3.2°]</td>
<td>50.7</td>
<td>50</td>
</tr>
</tbody>
</table>

through SDC and CDC.

2.3.3 Inner hodoscope (IH)

IH was the scintillator hodoscope with 120 mm long and 5 mm thickness, and segmented by 6 pieces at both left and right side as shown Fig.2.8. The scintillation photons are guided to outside of the magnet by optical fiber cable and amplified by 1 inch PMT to avoid the effect of the magnetic field. Because the counting rates were very high, the additional high voltages were provided to last 2 dynodes to avoid the decreasing of the gain.

IH was used not only as time of flight counters but also as a time 0 counters in the trigger. Dynamic range of the energy deposit at IH should be large from 1 MeV for minimum ionizing particle to 10 MeV for proton of low momentum of 200 MeV/c. For trigger counters, CFD (Constant Fraction Discriminator) were used to prevent time walk from the large difference of pulse height, on the other hands, timing signal discriminated by LED (Leading Edge Discriminator) were sent to TDC for TOF measurement. Time walk was corrected in the offline analysis as described in Sect.3.2.

2.3.4 Outer hodoscope (OH)

OH are scintillation hodoscope, where 2 PMTs are mounted at both ends of each scintillator, segmented by 17 pieces at both left and right side as described in Fig.2.4. The sizes are about 600 mm height, 10 mm thickness, and typically 150 mm width. For
2.3. Neutral kaon spectrometer (NKS)

The OH in the magnet gap, the scintillation photons are guided to outside of the magnet by fiber cable and amplified by 2 inch PMTs. The PMTs are shielded by isolated iron cylinders to reduce the effect of magnetic field.

The signals of OH are used to make trigger signal. In analysis, the informations of the time of flight are achieved from corrected TDC of IH and OH and the vertical positions of charged particles are evaluated by the time differences of the signal from up- and downside PMTs.

2.3.5 Electron veto counter (EV)

EV are scintillation counters and set to suppress the background from $\gamma \rightarrow e^+e^-$ process in trigger level. They cover vertically $\pm 2.5$ cm to the horizontal plane involving beam line at OH position. The geometrical acceptance is reduced about 8%.

2.3.6 Sweep magnet

To suppress the serious background from the $e^+e^-$ pair creation, a sweep magnet was set between the radiator and NKS. Furthermore, helium bag occupied from the sweep magnet to front of target. Besides, to remove the beam halo, a collimator was arranged just in front of the sweep magnet. The collimator was made from lead, and its hall was diameter of 1.0 cm and length of 30 cm. Although the materials in upper stream were less than those at target, $e^+e^-$ generated at upper stream met the trigger condition easily. Hence, the materials in upper stream had to be as small as possible so as to suppress the background in trigger level. On the other hand, $e^+e^-$ generated at target caused the large single rates on each detectors. Thus, the conditions of the trigger rate and operation of the detectors, especially drift chambers, limited the beam intensity.
2.4 Target system

we used a liquid deuterium target in order to investigate the elementary process of the photo-production of neutral kaon on a neutron.

The target system which controlled the liquefaction of the deuterium and kept the liquid state were adapted to NKS. The target system was designed with attention to maximizing the yield of $K^0$, minimizing the background and safety of operation. For the $K^0$, target thickness was optimized and density of the liquid deuterium was kept as high as possible. For the background, the amount of material around the target had to be reduced. Concerning safety operation, the system was controlled remotely by LabVIEW program running on a Linux machine in the experimental hall, and we could operate and monitor it from measurement room via network.

The temperature around a liquid target and the pressure of the residual gas were monitored all through the period of experiment, and the density of the target was estimated with small statistic and systematic error.

2.4.1 Design of target system

The outline figure of target system is shown at Fig. 2.9. Although the target cell was placed at center of NKS, the refrigerator should be placed outside of the magnet because the space around target was quite limited. The long cylindrical part of the cryostat was inserted in the vertical hole with an inner diameter of 120 mm at the center of the yoke and pole. At the top of the cryostat, 2-Stage Gifford-McMahon refrigerator (Sumitomo Heavy Industry RD-208B) was placed. The ultimate temperature of the first and second stage were measured as 9.2 K and 38.1 K, respectively, in the manufacturer’s examination. Figure.2.10 shows the load map of the capacity of this refrigerator. The cooling powers of two stages were 20 W at 50 K and 8 W at 20 K, respectively. At the second stage of the refrigerator, an oxygen-free copper rod was attached to extend its stage to the center of NKS. Two heat exchangers, condenser and re-condenser, were located at the end of the copper rod. The deuterium was liquefied at the condenser and then dropped into the target cell. The re-condenser worked to liquefy the evaporated deuterium from the cell. The refrigeration power of the first stage was also used to cool the thermal shield made of aluminum alloy. The heat transfer to the radiation shield was estimated to be 3.7 W in the condition that the surrounding temperature was 300 K, temperature of the shield was 50 K, and the vacuum of the cryostat was $1.8 \times 10^{-3}$ Pa. The heat transfer to the copper rod was 0.6 W when the temperature of the rod was 18 K in the above condition.

2.4.2 target cell

The cell in which the liquid deuterium is accumulated is shown Fig.2.11. The holder is made of aluminum with 1mm thickness and the windows on the beam line are mylar film with 75μm thickness in order to reduce the background from e+e- pair creation and the effect of the multiple scattering of charged particle.

The inside diameter of open parts of the target cell are 40 mm, which is decided from
Figure 2.9: Schematic view of the target system.

Figure 2.10: Schematic view of the target system.
beam size of about 5 mm in $\sigma$ and that the fluctuation of position of the beam spot is less than 5 mm.

When the cell is filled by the liquid deuterium, the mylar windows expanded due to the pressure. Its effect is estimated from the data analysis and calculation by finite element method, and achieved about 1 mm expansion for both windows. Therefore the target width is evaluated 34 mm ± 2 mm along the beam line.

![Figure 2.11: The picture of target cell.](image)

### 2.4.3 Equipment

A 50 W heater and a temperature sensor were placed on the copper rod. The temperature was controlled by feeding back the measurement of sensor to heater. Two more temperature sensors were placed to measure the temperature of the gas or the liquid directly. One sensor was placed in the pipe between the re-condenser and the target cell. The other one was placed in the cell. These kind of temperature sensors have low sensitivity to the magnetic field and high resistance to ionizing radiations.

The temperature of liquid deuterium was about 19 K and changed within ± 0.1K. The pressure of the residual gas was near 50 kPa and changed within ± 2 kPa. The density of the liquid deuterium target is evaluated from the temperature and pressure by rule of thumb(Appendix A). The density is estimated 0.17 g/cm$^3$ typically (Sect.3.9.3).
2.5 Data acquisition system

2.5.1 setup

The counting house was located on the ground far from the experimental hall, therefore signals from detectors were sent through 50~70 m cables except for the discriminated signals from drift chambers and tagger. Analog signals were sent by RG58/U except for ones from IH which were sent by RG8/U. Attenuation of the signal height through these cables were typically 70% or 80%.

The signals of IH, OH and EV were digitized in counting house to be used to make triggers and sent to TDC. For IH, the signal was divided before digitization and the mate was sent to ADC. For OH and EV, the signals were divided at PMT in experimental hall and the mate were sent to ADC through 100 m long cable.

On the other hand, tagger signals were digitized in experimental hall and taken a coincidence between TagF and TagB. We could change the mode whether the coincidence was taken by relay switch from the counting house. Thus, logic signal of TagF was sent to TDC in counting house, in contrast, logic and raw signal of TagB were sent to TDC and ADC, respectively.

The signal of drift chamber was amplified by pre-amp on chamber and digitized by amp-discriminator in experimental hall. Section 2.5.3 mentions as for chamber read out system.

Figure 2.13 shows a diagram of the data acquisition system. The system operated synchronously to the accelerator cycle. The data for IH, OH, EV and tagger were fed into the TDC and ADC modules of the TKO or CAMAC. The data in TKO were then

Figure 2.12: target position in the vacuum chamber.
stored in VME memory module (SMP). The SMP had dual memory and exchanged the roles of storing and reading event by event to take data efficiently.

![Data acquisition system](image)

**Figure 2.13:** Data acquisition system.

### 2.5.2 Trigger logic

The trigger conditions of this experiment are shown in Table 2.4, and trigger logic is shown in Fig.2.14.

The main trigger (MT) logic was generated of 3 parts.

\[ MT = LEFT \otimes TIGHT \otimes BEAM \]

**Beam**: The trigger for that the photon was generated in the energy region of 0.8 to 1.1 GeV and generated charged particles.

**Left or Right**: Left or Right trigger corresponding to that more than one charged particles passed through IH, DC and OH.

To reject the \( e^+e^- \) background events, electron veto counters were required at both Left and Right trigger.

For tagger calibration run, only tagger trigger was used as main trigger. This trigger was not biased by conditions of NKS side.
2.5. DATA ACQUISITION SYSTEM

<table>
<thead>
<tr>
<th>Component</th>
<th>Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>MainTrigger</td>
<td>$MT = \text{LEFT} \otimes \text{RIGHT} \otimes \text{Beam}$</td>
</tr>
<tr>
<td>Left Trigger</td>
<td>$\text{LEFT} = \text{IHL} \otimes \text{OHLU} \otimes \text{OHLD} \otimes \text{EVL}$</td>
</tr>
<tr>
<td>Right Trigger</td>
<td>$\text{RIGHT} = \text{IHR} \otimes \text{OHRU} \otimes \text{OHRD} \otimes \text{EVR}$</td>
</tr>
<tr>
<td>Beam Trigger</td>
<td>$\text{BEAM} = (\text{IHL} \otimes \text{IHR} \otimes \text{SUM})$</td>
</tr>
<tr>
<td>Tagger (B: Backup Counter)</td>
<td>$\text{TagB} = \text{TagB1} \oplus \cdots \oplus \text{TagB12}$</td>
</tr>
<tr>
<td>(F: Finger Counter)</td>
<td>$\text{SUM1} = \text{TagB1} \otimes (\text{TagF1} \oplus \cdots \oplus \text{TagF4})$</td>
</tr>
<tr>
<td></td>
<td>$\text{SUM} = \text{SUM1} \oplus \cdots \oplus \text{SUM12}$</td>
</tr>
<tr>
<td>Left Side (U: up, D: down)</td>
<td>$\text{IHL} = \text{IHL1} \oplus \cdots \oplus \text{IHL6}$</td>
</tr>
<tr>
<td></td>
<td>$\text{OHLU} = \text{OHLU1} \oplus \cdots \oplus \text{OHLU17}$</td>
</tr>
<tr>
<td></td>
<td>$\text{OHLD} = \text{OHLD1} \oplus \cdots \oplus \text{OHLD17}$</td>
</tr>
<tr>
<td></td>
<td>$\text{EVL} = \text{EVLF} \oplus \text{EVLB}$</td>
</tr>
<tr>
<td>Right Side</td>
<td>$\text{IHR} = \text{IHR1} \oplus \cdots \oplus \text{IHR6}$</td>
</tr>
<tr>
<td></td>
<td>$\text{OHRU} = \text{OHRU1} \oplus \cdots \oplus \text{OHRU17}$</td>
</tr>
<tr>
<td></td>
<td>$\text{OHRD} = \text{OHRD1} \oplus \cdots \oplus \text{OHRD17}$</td>
</tr>
<tr>
<td></td>
<td>$\text{EVR} = \text{EVRF} \oplus \text{EVRB}$</td>
</tr>
</tbody>
</table>

Table 2.4: Trigger conditions.

Figure 2.14: Trigger logic long long ago

2.5.3 chamber read out system

The basic read out system was same used at INS-ES. A high voltage was applied to the sense wires through 16 channel register-capacitor (RC) cards. The signals on the sense wires were amplified by charge sensitive preamplifiers[34]. These RC and preamplifier cards were mounted on both end plates of CDC.
2.6 Data summary

The experiments were carried out at September, November, December in 2003 and April, May, June in 2004. Each periods was about 2 or 3 weeks. The duty factor was about 60% with 20 second of flat top time as shown in Fig.2.3. The radiator was inserted for 18 second.

The intensity of beam was from 2 to 3 MHz in the region from 0.8 to 1.1 GeV photon energy.

Table

<table>
<thead>
<tr>
<th>period</th>
<th>target</th>
<th>#spill</th>
<th>#photon</th>
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</thead>
<tbody>
<tr>
<td>September</td>
<td>liq. $D_2$</td>
<td>9.7E3</td>
<td>5.6E11</td>
</tr>
<tr>
<td></td>
<td>empty target</td>
<td>2.1E3</td>
<td>7.5E10</td>
</tr>
<tr>
<td></td>
<td>liq. $D_2$</td>
<td>6.3E3</td>
<td>3.2E11</td>
</tr>
<tr>
<td>November</td>
<td>liq. $D_2$</td>
<td>2.7E4</td>
<td>8.5E11</td>
</tr>
<tr>
<td>December</td>
<td>liq. $D_2$</td>
<td>1.6E4</td>
<td>5.4E11</td>
</tr>
<tr>
<td>April</td>
<td>liq. $D_2$</td>
<td>1.9E4</td>
<td>7.4E11</td>
</tr>
<tr>
<td>May</td>
<td>liq. $D_2$</td>
<td>3.9E4</td>
<td>1.6E12</td>
</tr>
<tr>
<td>June</td>
<td>liq. $H_2$</td>
<td>2.9E4</td>
<td>1.2E12</td>
</tr>
</tbody>
</table>

Table 2.6: Data summary of tagger trigger run.

<table>
<thead>
<tr>
<th>period</th>
<th>run name</th>
<th>#run</th>
</tr>
</thead>
<tbody>
<tr>
<td>September</td>
<td>tagging efficiency tagger</td>
<td></td>
</tr>
<tr>
<td>November</td>
<td>tagging efficiency tagger</td>
<td></td>
</tr>
<tr>
<td>December</td>
<td>tagging efficiency tagger</td>
<td></td>
</tr>
<tr>
<td>April</td>
<td>tagging efficiency tagger</td>
<td></td>
</tr>
<tr>
<td>May</td>
<td>tagging efficiency tagger</td>
<td></td>
</tr>
<tr>
<td>June</td>
<td>tagging efficiency tagger</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.5: Data summary of normal data taking for each experimental period.
Chapter 3

Analysis

3.1 Outline

The goal of the analysis in the present experiment is to obtain the differential cross section of $K^0$ photo production and compare with theoretical calculations. In this chapter, those procedures are described.

We measured events in which at least two charged particles were detected by TOF counters and drift chambers. The invariant mass of $K^0$ is calculated as following formula,

$$ M(\pi^+\pi^-)^2 = \left( \sqrt{p_\pi^+}^2 + m_\pi^+ + \sqrt{p_\pi^-}^2 + m_\pi^- \right)^2 - (\vec{p}_\pi^+ + \vec{p}_\pi^-)^2, $$

where $\vec{p}$ is a 3-momentum and $m_\pi$ is a mass of pion $()$ respectively.

The momentum of the charged particles is calculated from the curvature of tracks, and the $\beta$ are calculated from the length of the tracks and TOF.

In sect.3.2, the way of calibration for hodoscope, IH,OH and tagger counters are explained, and so performances of hodoscope are shown.

Calibration and performance of drift chambers are shown in sect.3.4, 3.5. Simultaneously, tracking method and momentum reconstruction are explained. The ways to suppress the background are explained in sect.3.6,3.7,3.8. Evaluating various efficiencies and calculating the cross sections are seen in sect.3.9.

3.2 Calibration of hodoscope

The time of IH, OH and TagB are corrected by a pulse height.

$$ Time_{corr} = Time - \frac{p_0}{dE - p_1} + p_2 $$

where $dE$ is energy deposit in a hodoscope, $p_0, p_1, p_2$ are fitting parameters, $Time_{corr}$ is corrected time, respectively. Although IH were used as time 0 counter in trigger level, relative difference of timing among IH existed within 1 nsec. Therefore, time difference
between each IH and each tagger are adjusted to be 0 run by run in analysis. Figure 3.1 shows the time difference distribution between IH and TagF when the multiplicity of TagF is 1. Details of analysis for tagger are described in Sect. ??.

The structure around 0 is caused by the beam bunch. The time resolution is about 420 psec in $\sigma$.

![Figure 3.1: Time difference between IH and tagger. The beam bunch structure of 2 nsec can be shown. The time resolution is about 420 psec in sigma](image1)

Figure 3.1: Time difference between IH and tagger. The beam bunch structure of 2 nsec can be shown. The time resolution is about 420 psec in sigma

Figure 3.2 shows the time difference between IHL and IHR when the particles tracks can be reconstructed and identified as pions (see Sect. ??). Fitting by the gaussian, the time resolution is estimated about 660 psec in $\sigma$.

![Figure 3.2: Time difference between IHL and IHR. The beam bunch structure of 2 nsec can be sown. The time resolution is about 660 psec in sigma](image2)

Figure 3.2: Time difference between IHL and IHR. The beam bunch structure of 2 nsec can be sown. The time resolution is about 660 psec in sigma

We required the time gates for these time difference distributions, $\pm 1.3$ nsec for IH-tagger and $\pm 2.0$ nsec for IHL-IHR, respectively. These gates width are corresponding to about 3 $\sigma$. 
In the case of OH, the time difference of between up and down give the information of vertical position, namely,

$$Z_{OH} = v \cdot \frac{(T_{down} - T_{up})}{2}$$

where $T_{up}$ and $T_{down}$ are corrected time, $v$ is the velocity of a light in the scintillator.

Figure 3.3 shows the vertical distribution at OHR1 when pions are selected. The dent at z=0 is due to EV.

![Graph showing vertical position distribution at OHR1 for selected pions.](image)

Figure 3.3: Distribution of vertical position at OHR1 for the events selected pions.

Moreover, time of flight (TOF) is measured from the time difference the mean time for up and down of OH to IH. The offset of mean time of OH are adjusted using the trajectory informations of the particles to give TOF correctly.

### 3.3 Calibration of tagger

### 3.4 Calibration of drift chamber

The drift chambers play essential role in this experiment because the momentum of charged particles are decided from the trajectory in the magnetic field. Furthermore, the vertex points of $K^0$ decay are reconstructed by the extrapolating from trajectories of 2 pions.
CHAPTER 3. ANALYSIS

Due to non uniformity of the electric field in drift space, the relation of drift length and drift times (X-T relation) is not linear. We assume that X-T relation is polynomial expression, 7th order for CDC and 4th order for SDC. The X-T relations are adjusted run by run. The parameters are decided for each layers. Fig.3.5 shows X-T relation for two layers in SDC and CDC respectively at a certain run.

3.5 Tracking of particle trajectory

The trajectory of charged particle in the magnetic field was calculated by the cubic spline interpolation method[35]. Because the vertical positions in drift chamber were not measured, fitting was carried out in mid-plane using vertical component of magnetic field at wire positions by least $\chi^2$ method, firstly. After OH corresponding to a track were found, vertical components of magnetic field off mid-plane were used in re-fitting.
3.5. TRACKING OF PARTICLE TRAJECTORY

assuming a trajectory connecting from origin point to vertical position at OH, in which horizontal positions on a track were known by previous fitting. In latter analysis, robust fitting method by J.W.Tukey[36] was used, which was a method finding a plausible track in consideration of weights for hits. The weights changed by residual calculated in previous fitting.

In these fitting, momentum of track was parameterized and defined from the tracking result.

The trajectory was extrapolated from DC to OH by 4th Runge-Kutta method, in which initial conditions were position and the derivative at outermost layer and momentum from fitting. In Runge-Kutta method, secondary derivative at each step was calculated using vertical component of magnetic field and initial momentum. The momentum was assumed not to be changed. Thus, the nearest OH were searched and labeled to the track. IH corresponding the track was searched by simply extension of a track. Figure.3.6 shows the residual distribution between a center of IH or OH and a point extrapolated from a track. The typical width of IH and OH are about 2.7 cm and 15 cm respectively(see sect.??,??). The cuts for these distribution are 1.6 cm and 10.0 cm respectively.

![Graph showing residual distribution](image)

Figure 3.6: The residual distribution between a center of hodoscope and a point extrapolated from track.

3.5.1 Momentum reconstruction

Particle momentum $p$ was calculated by

$$p = \sqrt{p_H^2 + p_V^2}$$
where \( p_H \) and \( p_V \) were horizontal and vertical momenta, respectively. \( p_H \) was calculated from the curvature of the trajectory measured by drift chambers. On the other hand, \( p_V \) was estimated from \( p_H \), \( Z_{OH} \) and flight length \((fl)\),

\[
p_V = p_H \cdot \frac{Z_{OH}}{fl}.
\]

\( fl \) was calculated by 4th Runge-Kutta method from DC to IH and OH.

### 3.5.2 Pre-selection before tracking

The procedure of pre-selections before tracking is presented in this section.

First, a selection by maximum hits in each layer (MLH) was applied. Figure 3.7 shows MLH distribution for Layer 1 and 14 in both side. Events with large MLH were

![Figure 3.7: MLH distribution for Layer 1 and 14 in both side.](image)

almost

### 3.5.3 Plane efficiency and residual resolution in a plane

Chamber plane efficiency and resolution are estimated for pions (figure 3.8). In these estimation, tracking is carried out except measured layer. To select the events as clear as possible, following conditions are required.

- \#hits of IH, OH, tagger = 1
- max layer hits of DC = 1
- \#tracks = 1 for both Left arm and Right arm
• hits for both side of measured layers except layer 1,15
• hits for 2 inside layers for layer 1,15
• pions are selected from relation between momentum and velocity (see Sect.3.6)

Efficiencies are typically 95% for CDC and 90% for SDC.

These resolutions include resolutions of trajectories. Therefore, to estimate the effects of tracking resolution, simulation data are analyzed assuming some resolutions (Fig.3.9). Figure.3.10 shows the ratio of resolutions of between plane and trajectory which are estimated by

\[ \sigma_{\text{calc}}^2 = \sigma_{\text{assume}}^2 + \sigma_{\text{trajectory}}^2. \]

\[ f = \sqrt{\sigma_{\text{calc}}^2 - \sigma_{\text{assume}}^2} / \sigma_{\text{assume}} \text{ for each layer} \]

In the range from 300 to 600 μm, the ratios are constant for each layers. Therefore, using these ratios, the resolutions of data are estimated as

\[ \sigma_{\text{measured}}^2 = \sigma_{\text{plane}}^2 + \sigma_{\text{trajectory}}^2 = (1 + f^2)\sigma_{\text{plane}}^2 \]

\[ \sigma_{\text{plane}} = \frac{1}{\sqrt{1 + f^2}} \sigma_{\text{measured}}. \]

Figure.3.11 shows results after subtraction of resolution of trajectories. Typical value of resolutions are 400μm for CDC and 500μm for SDC.

Figure.3.12 shows \( \chi^2 \) distribution for events selected pions assuming the position resolution of 300 μm for each layers. For detecting \( K^0 \), we apply the cut of \( \chi^2 < 8 \) for 2 tracks.

### 3.6 Particle Identification

The process \( \gamma \rightarrow e^+ e^- \) was the most largest background. In analysis, \( e^+ e^- \) generated upper stream were removed by vertex point reconstruction. Figure.3.13 shows vertex point distribution along beam line. The structures in upper stream are corresponding to the step size of Runge-Kutta method used to extrapolation of trajectory. When opening angle is very small and curvature is small, vertex point tends to be calculated at extrapolated point on trajectory. Because the acceptance for \( e^+ e^- \) events generated near target is much smaller than that generated in upper stream, most of \( e^+ e^- \) events are removed by selection of vertex point. Furthermore, the opening angle of \( e^+ e^- \) is very small, \( \cos \theta \sim 1 \), on the other hand, the opening angle of \( \pi^+ \pi^- \) from \( K^0 \) is relatively large.

Figure.3.15 shows the opening angle distribution for \( K^0 \) by simulation (conditions of simulation are explained in Sect.3.8.2). The opening angle of \( K^0 \) is less than 0.8, kinematically. Applying the cut of \( \cos \theta < 0.8 \), almost all \( e^+ e^- \) events are removed.

Because reconstruction of vertex points is not good for events with large opening angle, we apply the opening angle cut, \(-0.9 < \cos \theta < 0.8\).
Figure 3.8: Plane efficiencies and residual resolutions for each planes.

Figure 3.9: Chamber resolutions evaluated by analysis for simulation data. Resolutions are assumed as 300, 420, 500, 600 μm, respectively.

Figure 3.10: Estimation of the ratios resolution for trajectories to that for plane for each layers. Resolutions are assumed as 300, 420, 500, 600 μm, respectively.

Figure 3.16 shows the scatter plot of beta inverse v.s. momentum of particles after applying cuts of opening angle and vertex point, $-0.9 < \cos \theta < 0.8$, $V_x > -3$ (cm). The sign of momentum represent the charge of particles. The type of particles are
3.6. PARTICLE IDENTIFICATION

Figure 3.11: Chamber resolutions for each layers before (top) and after (bottom) subtraction of resolutions of trajectories.

Figure 3.12: $\chi^2$ distribution for pions. Top for Left arm, bottom for Right arm, respectively.

identified by selecting the regions surrounded solid lines. These regions are represented
Figure 3.13: Vertex points distribution along beam line. The structure in upper stream are due to analysis method. The distance among structures are corresponding to the step size of Runge-Kutta method used to extrapolation of trajectory.

Figure 3.14: Upper panel shows vertex point distribution along beam line is shown. Lower panel shows the differential of vertex point distribution and fitting result using two gaussian. Vertex point resolution is estimated about 1.3 mm.

as following formula,

\[
0.5 < \frac{1}{\beta} \\
\pm 0.144/(1/\beta - 0.2) - 0.08 \lessapprox p \lessapprox \pm 0.5/\sqrt{1/\beta^2 - 1} \quad \text{for } \pi^\pm,
\]
Figure 3.15: Opening angle distribution for $\pi^+\pi^-$ from $K^0$ estimated by simulation.

\[ 0.5/\sqrt{1/\beta^2 - 1} < p < 2.5/\sqrt{1/\beta^2 - 1} \] for proton.

Figure 3.16: The scatter plot of beta inverse v.s. momentum. The sign of momentum represent the charge. To eject the electrons and positrons, the events are required that a vertex can be reconstructed from two tracks and its opening angle, $\theta_{OA}$, are $\theta_{OA} < 0.8$. 
3.7 Event selection

When two trajectories are achieved, a vertex point can be reconstructed on an intersection point of extrapolations of these trajectories. Figure 3.17 shows the method of vertex reconstruction. We apply a cut to the distance of two tracks,

\[ dist < 0.0001 \] cm (Fig. 3.18).

![null](null)

Figure 3.17: Distance between two tracks.

![null](null)

Figure 3.18: The distribution of the distance of two tracks at vertex.

Figure 3.19 shows the vertex point distribution around the target for \( \pi^+\pi^- \) events. Figure 3.20 shows the distribution on beam line. In these figure, arrangement of the materials around a target are drawn. That almost all events come from the target, vacuum chamber and mylar film can be seen.

Figure 3.21 shows invariant mass spectrum for the events reconstructed the vertex points in target region and decay volume. For events in target region, huge background
of non-strangeness process, e.g. $\rho$, nucleon resonances, multi pion production, etc, exist, thereby $K^0$ events are not seen in the invariant mass spectrum. In contrast, selecting events reconstructed vertex out of target, a peak of $K^0$ can be clearly seen because the life time of $K^0$, $c\tau \sim 2.68$ cm, is relatively longer than that of other processes which decay immediately. Thus, we define the Decay Volume for searching $K_s^0$ as following formula,

$$r = \sqrt{(VT_x - 2.0)^2 + VT_y^2} < 5.0 \text{ (cm)};$$

where $VT_x$ and $VT_y$ are the coordinates in the frame in which the center of target is origin.

Besides, suppressing the background, the generating points of $K^0$ are calculated so as to select events generating in target. Cut conditions are

$$1.8 < dlen < 5.5 \text{ (cm)}$$

$$|G_x| < 1.8, \quad |G_y| < 2.5,$$

where $G_x$ and $G_y$ are generating points measured from the center of target, and $dlen$ is the distance between generating point and the center of target as shown in Fig.3.22.

### 3.8 Estimation of the background

In fig.3.21, the backgrounds exist in the $\pi^+\pi^-$ invariant mass spectrum even for decay volume, and the ratio of signal(S) to noise(N), S/N, is about 1 in the mass gate of 0.46 to 0.54 GeV/c$^2$. The origin of these background are considered as

**case 1** leakage from the target region due to the finite resolution of the reconstruction of vertex points.

**case 2** mismatch of the combination, $\pi^+$ from $K^0$ and $\pi^-$ from $\Lambda$.

#### 3.8.1 case 1

The background of case 1 is estimated from experimental data which are reconstructed vertex points in the target region, because it is considered that the kinematics of this background are almost same with those of events from target region.

#### 3.8.2 case 2

The background of case 2 is estimated by GEANT4 simulation. The conditions are

$E\gamma$: according to the cross section of bremsstrahlung at electron beam energy of 1.2 GeV.
**Fermi momentum of neutron**: according to Hulthen wave function in which parameters are decided reproduce the experimental data([?]).

\[ P(p) = \frac{K}{[(\alpha^2 + p^2)(\beta^2 + p^2)]^2} \]

where, \( P \) is the distribution of momentum density, \( p \) is momentum of neutron (GeV/c), \( K, \alpha, \beta \) are parameters and decided by fitting, \( K = 1.59E-5, \alpha = 4.86E- \)
Figure 3.21: $\pi^+\pi^-$ invariant mass spectrum in the target region (up) and in the decay volume (down).

Figure 3.22:

$2 \text{ (GeV/c)}, \beta = 0.22 \text{(GeV/c)}$. Figure 3.23 shows the fitting result for neutron momentum density distribution. Angular distribution is assumed to be isotropic.
Excitation function: assuming the cross section increasing linearly. The function is decided by fitting the cross section of $K^+$ data ([37], Fig. 3.24) so as to include the tendency of the cross section.

$K^0\Lambda$ are generated $1.4 \times 10^7$.

![Figure 3.23: Fitting of the momentum density distribution of neutron by Hulthen wave function.](image)

![Figure 3.24:](image)
Figure 3.25 show the invariant mass spectrum for $\pi^+\pi^-$ from simulation data. The shape of the combination mismatch events in invariant mass are evaluated.

![Invariant mass spectrum](image)

**Figure 3.25:** Invariant mass spectrum from simulation. The contamination of the combination of $\pi^+$ from $K^0$ and $\pi^-$ from $\Lambda$ are shown (dotted line), $\pi^+\pi^-$ from $K^0$ (dashed line).

Then, invariant mass from data (Fig.3.21) are fitted using the gaussian for the peak of $K^0$ and the shapes of two backgrounds which are only scaled in the three photon energy regions, that is $0.8 < E_\gamma < 0.9, 0.9 < E_\gamma < 1.0, 1.0 < E_\gamma < 1.1$ (Fig.3.26).

![Invariant mass spectra](image)

**Figure 3.26:**
3.9 Differential cross section

The differential cross section is estimated by

$$\frac{d\sigma}{d\Omega dp} = \frac{N_{\text{yield}}(p, \theta)}{N_{\gamma \text{ on target}} \cdot N_{\text{target}} \cdot \epsilon_{\text{acceptance}} \cdot \epsilon_{\text{DAQ}} \cdot \epsilon_{\text{track}} \cdot \epsilon_{\text{Gate}} \cdot 2\pi d \cos \theta dp}$$

where $N_{\text{yield}}$, $N_{\gamma \text{ on target}}$ and $N_{\text{target}}$ is number of selected events, photons bombarded on target and targets, $\epsilon_{\text{acceptance}}$ is acceptance of NKS, $\epsilon_{\text{DAQ}}$, $\epsilon_{\text{track}}$ and $\epsilon_{\text{Gate}}$ are efficiency of data taking, tracking analysis and gating spectrum.

The analysis efficiency is reduced as

$$\epsilon_{\text{track}} = \epsilon_{\text{MLH}} \cdot \epsilon_{\text{tracking}} \cdot \epsilon_{\text{track selection}}$$

where $\epsilon_{\text{MLH}}$, $\epsilon_{\text{tracking}}$ and $\epsilon_{\text{track selection}}$ are cut efficiency of max layer hit selection, track finding efficiency and good track selection efficiency, respectively. Estimation of each efficiency are described in Sect.3.9.4.

The efficiency of gating is reduced as

$$\epsilon_{\text{Gate}} = \epsilon_{\text{GateForTimeDifference}} \cdot \epsilon_{\text{GateForIM}}$$

where $\epsilon_{\text{GateForTimeDifference}}$ is efficiency of gating for the time difference between IHL and IHR or between TagF and IH, $\epsilon_{\text{GateForIM}}$ is efficiency of gating for invariant mass spectrum.

Number of photon is estimated from scaler counts by correcting as follows

$$N_{\gamma \text{ on target}} = f_{\text{att}} \cdot \epsilon_{\text{tagging}} \cdot \epsilon_{\text{tagger analysis}} \cdot N_{\gamma}$$

where $f_{\text{att}}$, $\epsilon_{\text{tagging}}$ and $\epsilon_{\text{tagger analysis}}$ is attenuation factor in the target and between target and calorimeter, tagging efficiency and tagger analysis efficiency, respectively. Estimation of these effect are described in Sect.3.9.2

The yields of $K^0$ and two backgrounds are corrected by same procedure, thus, the contributions of backgrounds are subtracted in a unit of cross section.

3.9.1 Evaluation of acceptance of NKS

Acceptance of NKS is evaluated by GEANT4 simulation program. The geometry of NKS is considered realistically. $K^0$ is generated in deuterium target with momentum of 0 to 1.0 GeV/c and cos $\theta$ of 0.5 to 1 uniformly in laboratory frame. The generating point is uniform in the target along beam line.

The same trigger with experiment is required, and the data is analyzed by the same analysis with experimental data. The chamber resolution of 400$\mu$m is assumed, which value is estimated in Sect.3.5. The plane efficiency of chamber and resolution of hodoscope are also assumed the estimated value from data. The number of generated $K^0$ is 40 million for the geometry of each experimental periods. The result is shown in Fig.3.27. Efficiency is maximum at forward region and the momentum region of about 300 MeV/c.
3.9. DIFFERENTIAL CROSS SECTION

![Graph showing differential cross section](image)

Figure 3.27: Acceptance map evaluated by GEANT4. Width of a bin is 0.02 GeV/c and 0.02 for $\cos \theta$.

![Graph showing contour plot](image)

Figure 3.28: Contour plot of acceptance map evaluated by GEANT4. Solid lines shows accepted region which have efficiency not too small.

3.9.2 Number of photons on target

Number of photons bombarded on target was estimated from scaler counts of tagger. These tagger signals are coincidence ones between TagF and TagB. The estimation must be included the effect as follows:

- Vanish of photons between radiator and target, especially, at a collimator positioned upstream sweep magnet,
- double count at neighbor segment,
- analysis cut
- attenuation in the target and between target and calorimeter.

First effect is named tagging efficiency ($\epsilon_{\text{tagging}}$), second and third are named tagger analysis efficiency ($\epsilon_{\text{taggeranalysis}}$), and last one is defined as attenuation factor ($f_{\text{att.}}$).

Tagging efficiency

Tagging efficiency was measured at the beginning and end (or after suspending the measurement due to any trouble) of each experimental periods in order to estimate the number of photon irradiated the target.
Tagging Efficiency is defined by

\[ \epsilon_{\text{tagging}} = \frac{N_{\text{calorimeter}}}{N_{\text{tagger}}} \]

where \( N_{\text{calorimeter}} \) and \( N_{\text{TagF}} \) are number of photons injected target and tagged with STB-tagger, respectively. At September 2003, we measured tagging efficiency by the CsI scintillation counter as calorimeter. It was positioned at 260 cm downstream from the center of NKS. (see Fig.3.29). We used the CsI and lead glass cerenkov counter (LG) at November 2003, and used only LG since December 2003. The position of the lead glass was the same as CsI. Figure.3.30 shows the correlation between a segment of TagF and ADC spectrum of Lead Grass measured at May 2004. ADC spectrum of Lead grass depends on TagF segment, that is, photon energy. Dents around TagF15 and TagF46 are due to supports at the window on the accelerator ring. \( N_{\text{calorimeter}} \) is estimated from ADC spectrum of Lead grass for each TagF segment.

Figure 3.29 shows tagging efficiencies of each experimental periods. Errors are statistical only. Decreases in efficiencies are found around TagF1-10 (high energy side for photon energy) and TagF35-48 (low energy side). In principle, the efficiencies for each segment should be equal because the photon interaction possibility between radiator and target is almost uniform in present energy region. The effect for high energy side is considered due to the noise trigger which are made by interaction with residual gas in accelerator ring. On the other hand, the effect for low energy side is considered due to supports at the window on the accelerator ring. These effects are not corrected since the situation is same with normal data taking in any beam intensity.

The ratio of the photon missed between the front of target and Calorimeter is estimated less than 1% by simulation.
3.9. DIFFERENTIAL CROSS SECTION

Figure 3.30: Correlation between a segment of TagF and ADC spectrum of Lead grass. Upper and right panels show the projection spectrum. Dents around TagF15 and TagF46 are due to supports at the window on the accelerator ring.

Analysis efficiency

In analysis as mentioned in Sect.3.3, to remove accidental coincidence between TagF and TagB, we apply various cuts for tagger. The effect is defined as tagger analysis efficiency, \( \epsilon_{\text{tagger analysis}} \).

The efficiency is estimated using tagger trigger run which is not biased by any condition from NKS side, and calculated from the ratio of number of events before cut to those after cut.

Figure 3.32 shows the beam intensity dependence of tagger analysis efficiency. These run was taken at beam intensity of 20 kHz, 130 kHz, 1.2 MHz, 1.8 MHz, 2.7 MHz, respectively. Obviously, the efficiencies depend on beam intensity. This is attributed to increase of accidental coincidence. When the cross section is estimated, tagger analysis efficiency is calculated by mean value of normal beam intensity runs for each experimental periods.

Attenuation factor

The attenuation factor, \( f_{\text{att.}} \), is estimated by calculation from radiation length of materials and by simulation. Both estimations result in almost same value, \( f_{\text{att.}} < 1 \% \), and so this effect is considered negligible.
Figure 3.31: Tagging Efficiency at each experimental periods.

Figure 3.32: Beam intensity dependence of tagger analysis efficiencies. When beam intensity is high, tagger analysis efficiency is low due to increase of accidental coincidence.
### 3.9.3 Number of Target

As mentioned in Sect. 2.4, the temperature of the liquid deuterium and the pressure of residual deuterium gas were monitored through experimental period. Thereby, the density of the liquid deuterium can be calculated. Because the fluctuations of the temperature and pressure did not much affect the density so that amount of deuterium target. In contrast, the change of the thickness of target due to the pressure of liquid deuterium was larger. The expansion of target is calculated by finite element method and evaluated about 1 ~ 2 mm for both side. Besides, the thickness of target during experiment can be estimated from data (Fig. 3.13), and so the consistent result with finite element method calculation is achieved. In addition, due to the fluctuation of circulating electron beam, the position irradiated photons on target changed slowly. It was corrected by adjustment of the way of moving radiator, and so the fluctuation of beam position on target was less than 5 mm. Figure 3.33 shows the dependence of number of neutrons on the position of photon beam and the expanding condition of mylar films. Because beam offset was 5 mm at the maximum in each experimental period, number of neutrons used in analysis are calculated by taking mean value between 0 to 5 mm. Table 3.2 shows typical physical values (detailed are discussed in Appendix.A).

#### Table 3.1: The typical value of tagging efficiency for each measurement. The values of 2nd column are the efficiency for tagF segment 1. The values of 3rd column are averaged for tagF from segment 10 to 48.

<table>
<thead>
<tr>
<th>period</th>
<th>minimum</th>
<th>average</th>
</tr>
</thead>
<tbody>
<tr>
<td>September ’03</td>
<td>0.73</td>
<td>0.80</td>
</tr>
<tr>
<td>November ’03</td>
<td>0.75</td>
<td>0.80</td>
</tr>
<tr>
<td>December ’03</td>
<td>0.75</td>
<td>0.80</td>
</tr>
<tr>
<td>April ’04</td>
<td>0.74</td>
<td>0.79</td>
</tr>
<tr>
<td>May ’04</td>
<td>0.74</td>
<td>0.78</td>
</tr>
</tbody>
</table>

#### Table 3.2: The list of number of deuteron. Most largest error is due to uncertainty of the thickness of target.

<table>
<thead>
<tr>
<th>month</th>
<th>density of D(_2) (g/cm(^3))</th>
<th>thickness (cm)</th>
<th>number of deuteron (barn(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>September</td>
<td>0.168 ± 0.001 (stat.)</td>
<td>3.1 ± 0.1 (syst.)</td>
<td>0.168 ± 0.001 ± 0.001</td>
</tr>
<tr>
<td>November ~ May</td>
<td>0.173 ± 0.001 (stat.)</td>
<td>3.1 ± 0.1 (syst.)</td>
<td>0.173 ± 0.001 ± 0.001</td>
</tr>
</tbody>
</table>
Figure 3.33: Number of neutrons for the deuteron density of 0.173 g/cm$^3$. Upper figure shows the schematic view of target cell. The expansion of mylar films are drawn exaggeratedly. Lower panel shows number of neutrons for each beam offsets and expanding condition. The points correspond to expansion of 3.0, 2.5, 2.0, 1.5, 1.0 mm in order from top.

### 3.9.4 Estimation of efficiencies

**DAQ efficiency**

A typical DAQ efficiency was 90 % for a trigger rate of 100 Hz. DAQ efficiencies for each experimental periods are mentioned in Table.3.3
Table 3.3: DAQ efficiencies for each month. In the latter half of september, because beam intensity was high, about 3~3.5 MHz, DAQ efficiency was lower than that of other period.

<table>
<thead>
<tr>
<th>month</th>
<th>DAQ efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>September (first half)</td>
<td>90.1 ± 0.04%</td>
</tr>
<tr>
<td>(latter half)</td>
<td>85.1 ± 0.03%</td>
</tr>
<tr>
<td>November</td>
<td>89.4 ± 0.02%</td>
</tr>
<tr>
<td>December</td>
<td>91.7 ± 0.03%</td>
</tr>
<tr>
<td>April</td>
<td>89.8 ± 0.04%</td>
</tr>
<tr>
<td>May</td>
<td>88.1 ± 0.02%</td>
</tr>
</tbody>
</table>

Table 3.4: Tracking efficiency for each month.

<table>
<thead>
<tr>
<th></th>
<th>September</th>
<th>November</th>
<th>December</th>
<th>April</th>
<th>May</th>
</tr>
</thead>
<tbody>
<tr>
<td>Left</td>
<td>97.40±0.07%</td>
<td>97.40±0.07%</td>
<td>97.38±0.09%</td>
<td>98.06±0.07%</td>
<td>98.00±0.05%</td>
</tr>
<tr>
<td>Right</td>
<td>96.88±0.11%</td>
<td>96.88±0.11%</td>
<td>96.92±0.13%</td>
<td>96.48±0.13%</td>
<td>97.67±0.06%</td>
</tr>
</tbody>
</table>

Tracking efficiency

Tracking efficiencies are estimated each hit of OH. To select events as clear as possible, we require that number oh hits of IH and OH are 1. Additionally, when the efficiency on Left arm is estimated, we require that the track in Right arm is identified as proton. Nevertheless, in forward and backward direction, there are electrons or positrons which does not through the chamber but hitting IH and OH, so the tracking efficiency is seen relatively low. The tracking efficiencies from OH segment 4 to 12 are nearly flat, then we use the mean value in this region as tracking efficiency. Table.3.4 shows the tracking efficiency for each layers.

Efficiency of cuts for $\chi^2$ and number of hits in a track

As mentioned in Sect.3.5, $\chi^2$ cut is applied for both tracks in Left arm and Right arm. Besides, it is required that number of hits in a track are larger than 7 for both tracks. Accordingly, efficiencies for these cuts are estimated. Firstly, efficiency for number of hits, $\epsilon_{\#hits}$ is estimated, and then efficiency for $\chi^2$ cut, $\epsilon_{\chi^2}$ is estimated.

$$\epsilon_{\#hits} = \frac{N_{\#hits>7}}{N}$$

$$\epsilon_{\chi^2} = \frac{N_{\#hits>7,\chi^2<8}}{N_{\#hits>7}}$$

The results are shown in Fig.?? , Fig.3.35 and Table.3.5. The efficiencies for the region of lower momentum are estimated relatively lower values due to geometrical conditions. Hence, we estimate efficiencies to be mean value in the momentum region from 300 to 500 MeV/c.
3.9.5 Systematic errors

Table.?? shows the typical values of efficiencies and its statistical or systematic errors.
Figure 3.35: Efficiency of $\chi^2$ cut for the experimental data (left) and simulation data (right). Top figure shows the efficiency for OH2, middle one for OH8 and bottom one for OH15. The solid lines represent estimated values.

Table 3.5: Efficiencies for number of hits and $\chi^2$ cuts. The efficiencies for experimental data are mean value among each periods because the differences among periods are small.

<table>
<thead>
<tr>
<th></th>
<th>#hits cut Left</th>
<th>#hits cut Right</th>
<th>$\chi^2$ cut Left</th>
<th>$\chi^2$ cut Right</th>
<th>total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experiment</strong></td>
<td>0.94</td>
<td>0.96</td>
<td>0.96</td>
<td>0.99</td>
<td>0.858</td>
</tr>
<tr>
<td><strong>Simulation</strong></td>
<td>0.995</td>
<td>0.995</td>
<td>0.98</td>
<td>0.95</td>
<td>0.922</td>
</tr>
</tbody>
</table>
Chapter 4

Result

In this chapter, experimental results are presented and compared with theoretical calculations mentioned in Chap.1. Firstly, experimental results are presented about angular distribution, momentum and photon energy dependence in Sect.4.1. Secondly, the calculation method of cross section on deuteron target is described in 4.2. Finally, experimental results are discussed comparing with the calculations in Sect.4.3

4.1 Experimental results

Laboratory angular distribution of the cross sections for $K^0$, two backgrounds and the results after subtracted background contributions are shown in Fig.4.1 in the photon energy regions of $0.9 < E_\gamma < 1.0$ and $1.0 < E_\gamma < 1.1$ GeV. As mentioned in Sect.3.9.1, we select three regions, Reg1, Reg2, Reg3, on acceptance map. Therefore, the cross sections in Fig.4.1 are calculated by

$$\frac{d\sigma}{d\Omega} = \int_{E_{\text{min}}}^{E_{\text{max}}} dE_{\gamma} \int_{\text{Reg1+Reg2+Reg3}} d\sigma d\Omega d\cos \theta \ [\mu b/\text{sr} \times 0.1\text{GeV}].$$

Next, momentum dependence of the cross sections are shown in Fig.4.2 in the photon energy region of $0.9 < E_\gamma < 1.0$ and $1.0 < E_\gamma < 1.1$ GeV.

$$\frac{d\sigma}{dp} = \int_{E_{\text{min}}}^{E_{\text{max}}} dE_{\gamma} \int_{\text{Reg1or2}} d\sigma d\Omega d\cos \theta \ [\mu b/(\text{GeV}/c) \times 0.1\text{GeV}].$$

4.2 Theoretical calculations

4.3 Comparison and discussion
Figure 4.1: Angular distribution after corrected efficiencies. Photon energy range is $0.9 < E_\gamma < 1.0$ (left side) and $1.0 < E_\gamma < 1.1$ (right side). Background from case 1 and case 2 are also drawn in upper figures. The results subtracted the background are shown in lower figures.

Figure 4.2: Momentum dependence after corrected efficiencies. Left side panels are Region 1 and Right side panels are Region 2. For each side panels, photon energy range is $0.9 < E_\gamma < 1.0$ (left) and $1.0 < E_\gamma < 1.1$ (right). Background from case 1 and case 2 are also drawn in upper figures. The results subtracted the background are shown in lower figures.
Figure 4.3:
Acknowledgement

\(\ (^{o^o})/^-^- \ < \text{Thank you} \)
Appendix A

Liquid deuterium

The number of neutrons is estimated as the following formula:

\[
N = \int L(x, y) \rho_n I(x, y) dS
\]

\[
L(x, y) = WidthOfCell + 2 \times (\sqrt{l^2 - (x^2 + y^2)} - l + d)
\]

\[
l = \frac{d^2 + RadiusOfCell^2}{d^2}
\]

\[
I(x, y) = \frac{1}{2\pi\sigma^2} \exp \left( -\frac{(x - x_0)^2 + (y - y_0)^2}{2\sigma^2} \right)
\]

\[
\rho_n = \frac{N_A}{M_{D_2}} \times 2 \times \rho_{D_2} \ [cm^{-3}]
\]

\[
N_A = 6.02 \times 10^{23} \ [mol^{-1}] , \ M_{D_2} = 2.014 \times 2 \ [g/mol]
\]

WidthOfCell = 30mm , RadiusOfCell = 40mm

\[
\sigma = 5mm
\]

\[
\rho_{D_2} = 0.168 , 0.173 \ [g/cm^3]
\]

\[
y_0 = 0
\]

\[
x_0 = 0 \sim 10mm \ by \ 1mm
\]

\[
d = 1.0 , 1.5 , 2.0 , 2.5 , 3.0mm
\]
Bibliography