Search for the \( K^{-}pp \) bound state via \( \gamma d \to K^{+}\pi^{-}X \) reaction at \( E_{\gamma} = 1.5–2.4 \) GeV

LEPS Collaboration

A.O. Tokiyasu \(^{a,n} \), M. Niiyama \(^{b} \), J.D. Parker \(^{b} \), D.S. Ahn \(^{a} \), J.K. Ahn \(^{c} \), S. Ajimura \(^{a} \), H. Akimune \(^{d} \), Y. Asano \(^{e} \), W.C. Chang \(^{f} \), J.Y. Chen \(^{a} \), S. Date \(^{g} \), H. Ejiri \(^{a} \), H. Fujimura \(^{ae} \), M. Fujiwara \(^{a,i} \), S. Fukui \(^{j} \), S. Hasegawa \(^{a} \), K. Hicks \(^{k} \), K. Horie \(^{a} \), T. Hotta \(^{a} \), S.H. Hwang \(^{l} \), K. Imai \(^{t} \), T. Ishikawa \(^{h} \), T. Iwata \(^{m} \), Y. Kato \(^{n} \), H. Kawai \(^{o} \), K. Kino \(^{a} \), H. Kohri \(^{a} \), Y. Kon \(^{a} \), N. Kumagai \(^{s} \), D.L. Lin \(^{i} \), Y. Maeda \(^{p} \), S. Makino \(^{q} \), T. Matsuda \(^{u} \), T. Matsumura \(^{i} \), N. Matsuoka \(^{a} \), T. Mibe \(^{a} \), M. Miyabe \(^{h} \), M. Miyachi \(^{s} \), N. Muramatsu \(^{h} \), R. Murayama \(^{t} \), T. Nakano \(^{a} \), Y. Nakatsugawa \(^{a} \), M. Nomachi \(^{t} \), Y. Ohashi \(^{g} \), H. Okkuma \(^{g} \), T. Ohta \(^{a} \), T. Ooba \(^{o} \), D.S. Oshuev \(^{f} \), C. Rangacharyulu \(^{u} \), S.Y. Ryu \(^{a,c} \), A. Sakaguchi \(^{t} \), T. Sawada \(^{a} \), P.M. Shagina \(^{v} \), Y. Shiino \(^{o} \), H. Shimizu \(^{h} \), E.A. Strokovsky \(^{ac} \), Y. Sugaya \(^{i} \), M. Sumihama \(^{w} \), J.L. Tang \(^{ad} \), Y. Toi \(^{i} \), H. Toyokawa \(^{g} \), T. Tsunemi \(^{b} \), M. Uchida \(^{x} \), M. Ungaro \(^{ab} \), A. Wakai \(^{y} \), C.W. Wang \(^{f} \), S.C. Wang \(^{l} \), K. Yonehara \(^{d} \), T. Yorita \(^{a,g} \), M. Yoshimura \(^{s} \), M. Yosoi \(^{a} \), R.G.T. Zegers \(^{aa} \)

\(^{a} \) Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan
\(^{b} \) Department of Physics, Kyoto University, Kyoto 606-8502, Japan
\(^{c} \) Department of Physics, Pusan National University, Busan 609-735, Republic of Korea
\(^{d} \) Department of Physics, Konan University, Kobe, Hyogo 658-8501, Japan
\(^{e} \) XFEL Project Head Office, RIKEN 1-1, Koto, Saitama, Hyogo 679-5148, Japan
\(^{f} \) Institute of Physics, Academia Sinica, Taipei 11529, Taiwan
\(^{g} \) Japan Synchrotron Radiation Research Institute, Sayo, Hyogo 679-5143, Japan
\(^{h} \) Research Center for Electron Photon Science, Tohoku University, Sendai, Miyagi 982-0826, Japan
\(^{i} \) Advanced Photon Research Center, Japan Atomic Energy Agency, Kizugawa, Kyoto 619-0215, Japan
\(^{j} \) Department of Physics and Astrophysics, Nagoya University, Nagoya, Aichi 464-8602, Japan
\(^{k} \) Department of Physics And Astronomy, Ohio University, Athens, OH 45701, USA
\(^{l} \) Advanced Science Research Center (ASRC), Japan Atomic Energy Agency (JAEA), Tokai, Ibaraki 319-1195, Japan
\(^{m} \) Department of Physics, Yamagata University, Yamagata 990-8560, Japan
\(^{n} \) Division of Particle and Astrophysical Sciences, Nagoya University, Furo-cho, Chikusa-ku, Nagoya-shi 464-8602, Japan
\(^{o} \) Department of Physics, Chiba University, Chiba 263-8522, Japan
\(^{p} \) Wakayama Medical College, Wakayama, Wakayama 641-8509, Japan
\(^{q} \) Department of Applied Physics, Miyazaki University, Miyazaki 889-2192, Japan
\(^{r} \) Department of Applied Physics, National Defense Academy in Japan, Yokosuka, Kanagawa 239-8686, Japan
\(^{s} \) Department of Physics, Tokyo Institute of Technology, Tokyo 152-8551, Japan
\(^{t} \) Department of Physics, Osaka University, Toyonaka, Osaka 560-0043, Japan
\(^{u} \) Department of Physics and Engineering Physics, University of Saskatchewan, Saskatoon, SK S7N 5E2, Canada
\(^{v} \) School of Physics and Astronomy, University of Minnesota, Minneapolis, MN 55455, USA
\(^{w} \) Department of Education, Gifu University, Gifu 501-1193, Japan
\(^{x} \) Department of Physics, Tokyo Institute of Technology, Tokyo 152-8551, Japan
\(^{y} \) Akita Research Institute of Brain and Blood Vessels, Akita 010-0874, Japan
\(^{z} \) Institute for Protein Research, Osaka University, Suita, Osaka 565-0871, Japan
\(^{aa} \) National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824, USA
\(^{ab} \) Department of Physics, University of Connecticut, Storrs, CT 06269-3046, USA
\(^{ac} \) Joint Institute for Nuclear Research, RU-141980 Dubna, Russia
\(^{ad} \) Department of Physics, National Chung Cheng University, Taiwan
\(^{ae} \) School of Medicine, Wakayama Medical University, Wakayama 641-0011, Japan

* Corresponding author.

0370-2693 © 2013 The Authors. Published by Elsevier B.V. Open access under CC BY license.
http://dx.doi.org/10.1016/j.physletb.2013.12.039
A search for the $K^-p$ bound state (the lightest kaonic nucleus) has been performed using the $γd → K^-π^-X$ reaction at $E_γ = 1.5–2.4$ GeV at LEPS/SPring-8. The differential cross section of the $K^-π^-$ photo-production off deuterium $(dσ/dcosθ_W/dσ^{pp}_W)$ has been measured for the first time in this energy region. A peak structure was searched for in the inclusive missing mass spectrum. A statistically significant peak structure was not observed in the region from 2.22 to 2.36 GeV/c$^2$. The upper limits of the differential cross section of the $K^-p$ bound state production were determined to be (0.17–0.55), (0.55–1.7) and (1.1–2.9) $μb$ at 95% confidence level with the assumed widths of 20 MeV, 60 MeV and 100 MeV.

© 2013 The Authors. Published by Elsevier B.V. Open access under CC BY license.

1. Introduction

Kaonic nuclei provide us with rich information on the sub-threshold $KN$ interaction and the nature of $Λ(1405)$ in the nuclear medium. Since the $KN$ interaction is strongly attractive in the isospin 0 channel, the existence of kaonic nuclei is supported theoretically. Many experiments have been performed to search for kaonic nuclei using various reactions. KEK-PS E471 reported theoretically. Many experiments have been performed to search for kaonic nuclei using various reactions. KEK-PS E471 reported experimentally, and there are two groups who have detected the positron in the missing mass spectra of $^4$He.

The shapes of the obtained spectra were compared with theoretical calculations, and the $K^-$ potential was derived to be rather deep (160–190 MeV). However, another theoretical calculation explained the spectra with a shallow (60 MeV) potential [5], and more intensive experimental investigations are needed to improve the precision of the shape analysis.

The lightest kaonic nuclei, $KN$, is fascinating to investigate the sub-threshold $KN$ interaction more precisely. In particular, the bound state consisting of $K^-$ and two protons ($K^-p$ bound state) has been actively studied because it has the largest number of $K^-$ pairs with $l = 0$ and is estimated to be the strongest binding system among the three-body systems.

The structure and the production mechanism of the $K^-p$ bound state have been investigated using various theoretical approaches [6–12]. The binding energy (B.E.) and the width ($Γ$) were predicted to be 9–95 MeV and 34–110 MeV, respectively. The predicted values are in considerable disagreement among the theoretical models depending on the $KN$ interaction models and the calculation methods. The $K^-p$ bound state has been searched for experimentally, and there are two groups who have detected the possible candidates. The first measurement was reported by FINUDA group at DAΦNE [13]. They investigated the stopped $K^-$ reaction on five kinds of targets of $^6$Li, $^7$Li, $^{12}$C, $^{27}$Al and $^{51}$V and observed a peak structure in the invariant mass spectrum of $Λ$ and proton emitted back-to-back from the targets. The B.E. and $Γ$ were determined to be $115^{+6}_{−5}(stat)^{+3}_{−4}(syst)$ MeV and $67^{+14}_{−13}(stat)^{+2}_{−2}(syst)$ MeV, respectively. There are some theoretical interpretations that the observed peak can be explained by the two-nucleon absorption with the final state interaction of outgoing particles [14]. DISTO group at SATURNE re-analyzed the dataset of the exclusive $pp → pK^+Λ$ reaction and observed a peak structure in the missing mass spectrum of $K^+$ [15]. The B.E. and $Γ$ were determined as $103 ± 3(stat) ± 5(syst)$ MeV and $118 ± 8(stat) ± 10(syst)$ MeV, respectively. These two measured values of B.E. and $Γ$ are different from each other. They are inconsistent with any of the existing theoretical predictions. Thus, the existence of the $K^-p$ bound state has not been established yet. New experiments using different reactions could help to resolve the controversial situation.

In this Letter, we report on the first search results using the $γd → K^-π^-X$ reaction in the photon energy region of $E_γ = 1.5–2.4$ GeV. A peak structure was searched for in the inclusive missing mass spectrum of the $d(γ,K^-π^-X)$ reaction by detecting $K^-$ and $π^-$ at forward angles in coincidence. The study of the inclusive spectrum allowed us to search for the $K^-p$ bound state without selecting the decay mode, whereas considerable contributions from quasi-free processes arise as the background in the search region ranging from 2.22 GeV/c$^2$ to 2.36 GeV/c$^2$. These background processes are also discussed.

If $K^-$ is detected at forward angles, $t$-channel reaction becomes dominant. $K^-$ or $K^*$ are expected to be exchanged in the framework of gauge-invariant effective Lagrangians [16]. A $K$ exchange is forbidden in the pion or kaon induced reactions, and it is one of the unique features of the photon induced reaction. Here, the exchanged $K$ or $K^*$ can be treated as virtual beam particles. From this viewpoint, $d(γ,K^-π^-X)$ reaction is regarded as the virtual $d(K^-π^-X)$ or $d(K^-π^-X)$ reaction, which have not yet been used for the search for the $K^-p$ bound state.

The production cross section of the $K^-p$ bound state is described as a function of the transferred momentum, $|t|$ [17]. If the $K^-p$ bound state is a compact object, the production cross section is expected to be enlarged at a large transferred momentum. On the other hand, if the $K^-p$ bound state is a soft object, the production cross section is expected to be enlarged at a small transferred momentum. By detecting $K^+$ and $π^-$ at forward angles, we searched for the $K^-p$ bound state in the small $|t|$ region from 0.1 to 0.4 (GeV/c)^2.

2. The LEPS experiment and analysis

The experiment was performed at LEPS/SPring-8 in 2002/2003 and 2006/2007. The experimental conditions and data qualities were similar throughout these two data-taking periods. Therefore two datasets were summed up for the analysis. Linearly polarized photons with the energy from 1.5 to 2.4 GeV were produced by the backward Compton scattering. The energy of each photon was measured by detecting the scattered electrons with a tagging counter. The photon energy resolution is estimated to be approximately 12 MeV. More details of the photon beam at LEPS/SPring-8 are given in Ref. [18].
Liquifized deuterium (LD2) of 16 cm effective length was used as the target. 7.6 \times 10^{12} tagged photons were incident on the target in total. Charged particles produced from the target were detected with the LEPS spectrometer at forward angles in the laboratory system. The LEPS spectrometer consists of a start counter (SC), a silica-aerogel Čerenkov counter (AC), a silicon vertex detector (SVTX), drift chambers (DCs), a dipole magnet with a field strength of 0.7 T and a time-of-flight (TOF) scintillator wall. AC has the refractive index 1.03 and was used for e^+e^- vetoes at the trigger level. The momentum threshold of AC is 2.0 GeV/c for kaons and 0.57 GeV/c for pions. The momenta of particles were determined using tracking information, and particle species were identified using TOF information. The momentum resolution is estimated to be 6 MeV/c at 1 GeV/c by the Monte Carlo simulation. Thus, the mass resolution of MM_d( K^+π^-) is \sim 10 MeV/c^2 in the region from 2.2 to 2.4 GeV/c^2. More details about the experimental setup are given in [19].

For the present analysis, events with K^+ and π^- tracks were selected with mass values required to be within 3σ, where σ is the mass resolution depending on the momentum. Events for which π^- was misidentified as K^+ were rejected by requiring that the missing mass of the p(γ, π^+π^-)X reaction was above 0.97 GeV/c^2, where the π^- mass was used instead of the K^+ mass. The misidentified events were distributed mainly in the region below 1.7 GeV/c^2 in the MM_d( K^+π^-) spectrum and were negligible in the region where a peak structures was searched for. To reduce the systematic uncertainty arising from the acceptance correction, the analysis was performed within the following kinematical region:

\[
\begin{align*}
\cos \theta_{K^+} &> 0.95 \\
\cos \theta_{\pi^-} &> 0.95 \\
0.25 \text{ GeV/c} < p_{K^+} &< 2.0 \text{ GeV/c} \\
0.25 \text{ GeV/c} < p_{\pi^-} &< 0.6 \text{ GeV/c} 
\end{align*}
\]

Here g^{lab}_{K^+} and g^{lab}_{\pi^-} denotes the scattering angle and momentum in the laboratory system, respectively. The vertex resolution along the beam axis was approximately 2 mm, and the events from the SC or AC were well-separated from the events from the LD2 target. The vertex points of the K^+ and π^- tracks were required to be located at the target. In addition, the distance of closest approach (DCA) between the two tracks was required to be less than 4 mm. These vertex constraints reduced the contribution of the hyperon decay events of which vertex points were outside the target or had large DCA values. The ratio of the signal of the K^-pp bound state to the background arising from the hyperon decay events was estimated to be improved by a factor of 2 by applying these vertex constraints. The event loss of the signal of the K^-pp bound state by these constraint was estimated to be 5% by the Monte Carlo simulation. Finally, for the events in which three tracks were detected (K^+, π^-, and p), the invariant masses of p and π^- (M(pπ^-)) were calculated, and the events in the range of 1.05 GeV/c^2 < M(pπ^-) < 1.12 GeV/c^2 were rejected because they arise from the quasi-free Λ production process. The event loss due to this cut is small (\sim 4%). There is little possibility to distort the shape of the spectrum of MM_d( K^+π^-).

3. Results and discussion

Fig. 1 shows the differential cross section spectrum of MM_d(K^+π^-) (d^2σ/dcosθ^{lab}_{K^+}dcosθ^{lab}_{π^-}/dM) within the kinematical region given in Eq. (1). The search region (2.22 GeV/c^2−2.36 GeV/c^2) and the K^-pp mass threshold (2.37 GeV/c^2) are also indicated in the figure.
Six processes were used for the background: the assumption that the \( \gamma \rightarrow \Lambda \ K^0 \) and \( \gamma \rightarrow \Sigma^0 \pi^+ \pi^- \), \( \gamma p \rightarrow \Sigma^+ K^- \pi^- \), \( \gamma p \rightarrow \Lambda(1520) K^- \), \( \gamma p \rightarrow \Lambda \pi^+ K^- \pi^- \), \( \gamma n \rightarrow \Sigma^+ \pi^- \pi^+ \pi^- \) and \( \gamma p \rightarrow \Sigma^0(1385)^+ K^- \pi^- \). The shapes of the spectra were generated with the GEANT-based Monte Carlo simulation, where the Paris-potential model was used to describe the momentum distribution of the nucleons inside the deuteron [20].

The yield of each background process was taken into account as a free parameter. The yield of the signal was increased from 0 to a certain value, and the Log-likelihood values was calculated at each point.

Fig. 2 shows the fit result with only background processes and the residue from the fitting function. \( \chi^2/\text{ndf} \) of the fit result is 1.4 in the range from 2.05 GeV/c\(^2\) to 2.6 GeV/c\(^2\), and approximately 1 in the range from 2.22 GeV/c\(^2\) to 2.36 GeV/c\(^2\). The tests were performed for signals with \( \Gamma = 20 \), 60 and 100 MeV, and 15 B.E. values ranging from 10 to 150 MeV. The signal shape was assumed to be the Breit–Wigner distribution with the fixed B.E. and \( \Gamma \) and was generated with the GEANT-based Monte Carlo simulation. As a result of tests, significant decrease of \(-2\Delta \ln L\) (twice the Log-likelihood difference of the hypotheses) was not observed under any assumption of B.E. and \( \Gamma \) values.

To quantitate the search results, the upper limits of the differential cross section of the \( K^- pp \) reaction as a function of assumed signal peak mass. The solid, broken and dotted lines are the results of \( \Gamma = 20 \) MeV, 60 MeV and 100 MeV, respectively.

The obtained yields were converted to the differential cross section of the typical hadron production processes such as the \( \gamma p/n \rightarrow K^+ \pi^- A \) or the \( \gamma p/n \rightarrow K^+ \pi^- \Sigma^0 \) processes within the kinematical region given in Eq. (1). As for the upper limits for \( \Gamma = 20 \) MeV, we can compare the obtained results with those given by the KEK-PS E471/ES49 experiment. The differences between the present and the KEK-PS E471/ES49 experiment are summarized as follows:

- The search object of the present study is the \( K^- pp \) bound state, while the KEK-PS E471/ES49 experiment aimed at the \( K^- pnn \) or \( K^- pnm \) bound states.
- The production mechanisms of kaonic nuclei are expected to be different between the photon induced and stopped \( K^- \) reactions.
• The present study is limited within the kinematical region given in Eq. (1).

However, two experiments are similar to each other in the aspect that peak structures were searched for in the inclusive missing mass spectra. KEK-PS E471/E549 group concluded that the formation probabilities of the four-body kaonic nuclei with narrow widths are less than a few percent per stopped kaon. Since absorbed $K^-$ in nuclei forms hyperons, their results are restated that the formation probabilities of kaonic nuclei are less than a few percent of the typical hyperon production cross section. The present results with an assumption of $20 $ MeV are comparable with the KEK results in terms of the ratio to the hyperon production cross section.

Though a peak structures was not observed, there were several thousand events in the search region. To investigate the background precisely, the $\text{MM}_{\pi^+}(K^+\pi^-)$ spectrum and the $\text{MM}_{\pi^0}(K^+)\text{p}$ spectrum were fitted simultaneously. The subscript "p" means that the missing mass was calculated using the proton mass for the target mass. The processes used for the fitting are listed in Table 1. The contribution of $K^0$ production is negligibly small under the selected kinematic conditions and was ignored. PDG values were used for the mass, the width and the branching ratio of the hyperon resonances [21], and all the processes were generated isotropically in the center of mass system in the Monte Carlo simulation. The mass and width of $\Sigma(1660)$ were assumed to be 1.66 GeV/c$^2$ and 0.1 GeV, respectively, and the branching ratios of the $\Lambda\pi^-$ and $\Sigma\pi^-$ decay modes were taken into account as free parameters. The fit result is shown in Fig. 5. The experimental data is shown as points with the error bars, and the fit results are shown as the red histograms. The total $\chi^2$/ndf for the fitting was 1.3. The fit result indicates that the main contribution to the $\text{MM}_{\pi^0}(K^+\pi^-)$ spectrum in the search region comes from the $\gamma p \rightarrow K^+\Lambda(1520)$ process. Its fraction of the observed yield is 22±3%. The contribution of the non-resonant $\Lambda/\Sigma\pi K^+\pi^-$ production is also estimated to be 24±5% in the search region.

The production cross section of the $K^-pp$ bound state was found to be small in the photon induced reaction, and it is difficult to separate the $K^-pp$ bound state signal from the background processes in the inclusive measurement. For the further study, it is necessary to detect the decay products of the $K^-pp$ bound state using the additional counters surrounding the target. The $K^-pp$ bound state is expected to have non-mesonic decay modes such as the $K^-pp \rightarrow \Lambda p$ or the $K^-pp \rightarrow \Sigma N$. In this case, the detection of proton or $\Lambda$ with a large transverse momentum is essential to reduce the contribution of background processes.

In addition to the search under the cut condition given in Eq. (1), searches for a peak structure were done in the different kinematical conditions as follows: (a) $|t| < 0.3 \text{ GeV/c}^2$, (b) $p_x < 0.8 \text{ GeV/c}$ and (c) $0.842 \text{ GeV/c}^2 < M(K^+\pi^-) < 0.942 \text{ GeV/c}^2$. Here, $p_x$ is the transferred momentum in the virtual $dK^-\pi^-X$ reaction, and $M(K^+\pi^-)$ is the invariant mass of $K^+\pi^-$. The cut conditions (a) and (b) correspond to selecting the especially small transferred momentum. The production cross section of the $K^-pp$ bound state is dependent on the kinematic condition, especially transferred momentum of the residual system. Although the production mechanism of the $K^-pp$ bound state is poorly understood, if the $K^-pp$ bound state was produced via the sticking process of the virtual $K^-$ or intermediate resonance states, the kinematic condition of small transferred momentum is expected to enlare the production cross section. The cut condition (c) corresponds to selecting $K^0$ production events. By applying the cut condition (c), the $K^-pp$ bound state was searched for in a different reaction channel: the $d\gamma, K^-\pi^0X$ reaction. If $K^0$ is produced at forward angles, the exchanged particle in the $t$-channel is limited to $K$ and $\pi$ [22]. A peak structure was searched for in the $\text{MM}_{\pi^0}(K^+\pi^-)$ spectrum under the conditions (a), (b) and (c), but no structure was observed again.

4. Conclusion

We searched for the $K^-pp$ bound state using the $\gamma d \rightarrow K^-\pi^-X$ reaction at $E_\gamma=1.5$–2.4 GeV. $K^-$ and $\pi^-$ were detected at forward angles. The differential cross section of the $K^-\pi^-$ photo-production off deuteron was measured for the first time in this energy region. A peak structure corresponding to the $K^-pp$ bound state was searched for in the inclusive $\text{MM}_{\pi^0}(K^+\pi^-)$ spectrum with the Log-likelihood ratio method. No peak structure was observed in the region from 2.22 to 2.36 GeV/c$^2$, and the upper limits of the differential cross section of the $K^-pp$ bound state production were determined to be (0.17–0.55), (0.55–1.7) and (1.1–2.9) $\mu b$ at 95% confidence level for $\Gamma=20, 60$ and 100 MeV, respectively. These values correspond to approximately 1.5–20% of the cross section of the typical hyperon photo-production. To study the origin of the background, the $\text{MM}_{\pi^0}(K^+\pi^-)$ spectrum and the $\text{MM}_{\pi^0}(K^0)$ spectrum were fitted simultaneously by including 15 background processes. The $\gamma p \rightarrow K^+\Lambda(1520)$ process

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Quasi-free processes.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton target</td>
<td>Neutron target</td>
</tr>
<tr>
<td>$\gamma p \rightarrow AK^+$</td>
<td>$\gamma n\rightarrow \Sigma^+K^+$</td>
</tr>
<tr>
<td>$\gamma p \rightarrow \Lambda(1405)K^+$</td>
<td>$\gamma n\rightarrow AK^+\pi^-$</td>
</tr>
<tr>
<td>$\gamma p \rightarrow \Sigma(1385)\Sigma^+$</td>
<td>$\gamma n\rightarrow \Sigma(1385)\Sigma^+$</td>
</tr>
<tr>
<td>$\gamma p \rightarrow \Sigma(1660)\Sigma^+$</td>
<td>$\gamma n\rightarrow \Sigma(1660)\Sigma^+$</td>
</tr>
<tr>
<td>$\gamma p \rightarrow \Lambda(1520)K^+$</td>
<td>$\gamma n\rightarrow \Lambda(1520)K^+\pi^-$</td>
</tr>
<tr>
<td>$\gamma p \rightarrow \Sigma(1385)\Lambda(1405)K^+$</td>
<td>$\gamma n\rightarrow \Sigma(1385)\Lambda(1405)K^+$</td>
</tr>
</tbody>
</table>
and the $\gamma N \rightarrow K^+\pi^-\pi\Lambda/\Sigma$ process were found to be the main contribution in the region from 2.22 to 2.36 GeV/$c^2$.

Acknowledgements

The authors thank the SPring-8 staff for their contributions in the operation of the LEPS experiment. This research was supported in part by the Ministry of Education, Science, Sports and Culture of Japan, by the GCOE program in Kyoto University, by the National Science Council of the Republic of China (Taiwan), by the National Research Foundation of Korea (2012R1A2A1A01011926) and by the National Science Foundation (NSF Award PHY-0244999). Author J.D. Parker was supported by a Postdoctoral Fellowship for Foreign Researchers from the Japan Society for the Promotion of Science.

References