Recent results of charged pion and kaon photoproduction on the proton at SPring-8/LEPS

H. Kohri[1,2,*] for LEPS Collaboration

[1]Research Center for Nuclear Physics, Osaka University, Ibaraki, Osaka 567-0047, Japan
[2]Nagoya University, Furocho, Chikusa, Nagoya 464-8602, Japan

Abstract. We carry out photoproduction experiments by using linearly polarized photon beams with energies of 1.5-3 GeV at SPring-8/LEPS. One of our physics motivations is to understand reaction mechanisms of hadron photoproduction. We study (1) $\vec{\gamma}p \to \pi^-\Delta^{++}$, (2) $\vec{\gamma}p \to \pi^+n$, (3) $\vec{\gamma}p \to K^+\Lambda(K^+\Sigma^0)$, and (4) $\vec{\gamma}p \to \pi^+\Delta^0$ reactions which produce (1) $u\bar{u}$, (2) $d\bar{d}$, (3) $s\bar{s}$, and (4) $d\bar{d}$ quark-antiquark pairs in the final state. Differential cross sections and photon beam asymmetries have been measured at forward meson angles of $0.6< \cos\theta_{cm} <1$. Precise comparison between the $\pi^-\Delta^{++}$ and $\pi^+\Delta^0$ reactions plays an important role in the study of nucleon resonances. It enables to distinguish between N^* and Δ^* by taking the cross section ratios of the two reactions. We have measured preliminary cross section ratios $d\sigma(\pi^+\Delta^0)/d\sigma(\pi^-\Delta^{++})$. The ratios are found to be close to 1/3, which is expected from the exchange of isospin=1 in the t channel, for $0.966< \cos\theta_{cm} <1$ and all the photon energies. The ratios become larger than 1/3 and close to 1 for larger angles and higher energy regions. The larger ratios might be due to Δ resonances, giving the ratio 4/3, excited in the intermediate state.

1 Introduction

In quark models, there are more nucleon resonances than those experimentally observed so far [1, 2]. Since nucleon resonances have relatively wide widths and are overlapping each other, rich physics observables with a wide angular and energy range are needed to search for new resonances. One of our physics motivations is to understand reaction mechanisms of hadron photoproduction. Nucleon resonances excited in the intermediate states of the reactions are very important to understand the reaction mechanisms.

We constructed a beamline for studying hadron photoproduction at a few GeV at SPring-8 in 2000. Linearly or circularly polarized photon beams were produced by backward Compton scattering of deep-UV laser lights with a wavelength of 257 nm and 8 GeV electron beams [3]. Recoil electrons were tagged to determine energies of the photon beams (1.5-3 GeV). The photon polarization was 88% at 3 GeV and 28% at 1.5 GeV. The photon beams were incident on a liquid hydrogen target with an effective length of 16 cm. Charged particles produced at forward angles were momentum-analyzed by the LEPS spectrometer [4]. Particle identification was performed by the mass calculated from the momentum and Time-Of-Flight. The LEPS spectrometer was optimized to detect a K^+K^- pair from a ϕ-meson at forward angles [5–11]. We also extensively studied kaon photoproduction reactions [12–19]. We newly installed a plastic scintillation counter to veto e^+e^- produced by the pair creation and no aerogel cherenkov counter was used in order to detect high momentum charged pions [20].

2 $u\bar{u}$, $d\bar{d}$, and $s\bar{s}$ productions

We precisely studied the (1) $\vec{\gamma}p \to \pi^-\Delta^{++}$ [21], (2) $\vec{\gamma}p \to \pi^+n$ [22], and (3) $\vec{\gamma}p \to K^+\Lambda(K^+\Sigma^0)$ [23] reactions. These reactions produce (1) $u\bar{u}$, (2) $d\bar{d}$, and (3) $s\bar{s}$ quark-antiquark pairs in the final states. Comparison among these reactions is of special importance to obtain a unified understanding of hadron photoproduction. Figure 1 shows the differential cross sections for the π^+n reaction [22].

The cross sections decrease monotonically as the photon beam energy increases for $0.6< \cos\theta_{cm} <0.9$. The energy dependence is different for $0.9< \cos\theta_{cm} <1$ and a small bump structure is observed for E_γ=1.5-2.2 GeV(W=1.9-2.2 GeV). The structure was also observed by DESY and was inferred to be due to nucleon resonances [24, 25]. In the nucleon resonance energies, CLAS measured the differential cross sections for wide angular regions and photon energies from 0.73 to 2.88 GeV [26]. Since the LEPS spectrometer is complementary to the CLAS spectrometer, the cross section data by LEPS are the first precise data for forward angles.

We also measured the differential cross sections for the $\gamma p \to \pi^-\Delta^{++}$ [21] and $K^+\Lambda(K^+\Sigma^0)$ [23] reactions. All the reactions have forward-peaking cross sections, which suggests the dominance of t-channel reaction mechanisms. The cross sections for the $\pi^-\Delta^{++}$ reaction by LEPS are the first high-statistics data. In the present data for the $K^+\Lambda(K^+\Sigma^0)$ reaction, the photon energy region was extended from 1.5-2.4 GeV [13] to 1.5-3 GeV [23].

*e-mail: kohri@rcnp.osaka-u.ac.jp

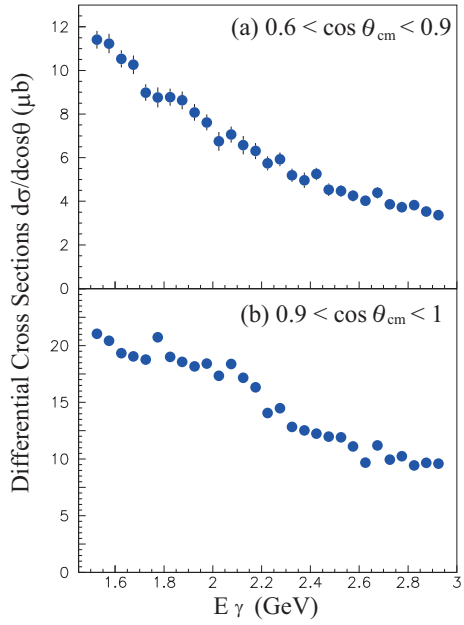

Figure 1. Differential cross sections for the $\gamma p \to \pi^+ n$ reaction for (a) 0.6< $\cos\theta_{cm}$ <0.9 and (b) 0.9< $\cos\theta_{cm}$ <1 [22].

The photon beam asymmetries obtained by using linearly polarized photon beams are sensitive to the reaction mechanisms. Figure 2 shows the asymmetries for the $\pi^+ n$ reaction for 0.6< $\cos\theta_{cm}$ <0.9 and 0.9< $\cos\theta_{cm}$ <1 [22]. The asymmetries are positive in this kinematical region, which is mostly explained by ρ-meson exchange in the t channel [27]. The asymmetries increase as the π^+ angle becomes smaller.

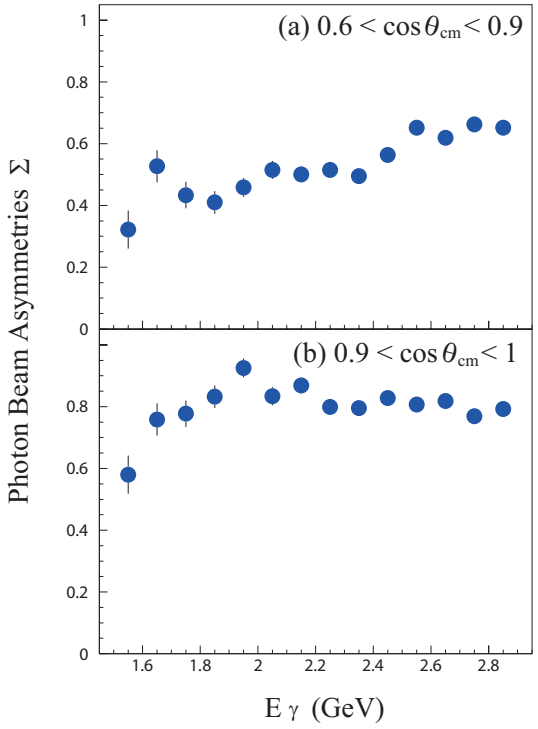

Figure 2. Photon beam asymmetries for the $\vec{\gamma} p \to \pi^+ n$ reaction for (a) 0.6< $\cos\theta_{cm}$ <0.9 and (b) 0.9< $\cos\theta_{cm}$ <1 [22].

The asymmetries for the $K^+\Lambda$ and $K^+\Sigma^0$ reactions [23] are also positive and smaller than those for the $\pi^+ n$ reaction. The positive asymmetries are mostly explained by K^*-exchange in the t channel [27]. Since the asymmetries gradually increase as the photon energy increases, the contribution from the K^*-exchange is inferred to become larger with increasing photon energy.

Figure 3 shows the asymmetries for the $\pi^-\Delta^{++}$ reaction [21]. It is interesting that only the $\pi^-\Delta^{++}$ reaction is found to have negative asymmetries in most of the present kinematical region. The negative asymmetries are explained by the dominance of π-exchange in the t channel [21]. In other pseudoscalar meson photoproduction reactions, such as $\vec{\gamma} p \to \pi^0 p$ [28, 29] and ηp [30, 31], positive asymmetries were observed at forward meson angles in this energy region. Pure $u\bar{u}$ quark-antiquark pair production might have different reaction mechanisms from the $d\bar{d}$ and $s\bar{s}$ productions. Negative asymmetries for the $\pi^-\Delta^{++}$ reaction are expected to be a key to obtain unified understanding of hadron photoproduction.

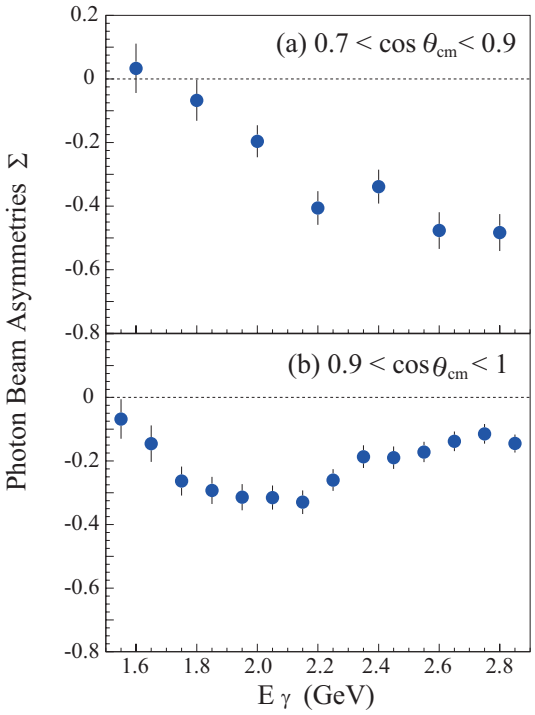

Figure 3. Photon beam asymmetries for the $\vec{\gamma} p \to \pi^-\Delta^{++}$ reaction for (a) 0.7< $\cos\theta_{cm}$ <0.9 and (b) 0.9< $\cos\theta_{cm}$ <1 [21].

3 Comparison between the $\gamma p \to \pi^-\Delta^{++}$ ($u\bar{u}$ production) and $\pi^+\Delta^0$ ($d\bar{d}$ production) reactions

The $\gamma p \to \pi^+\Delta^0$ reaction, which produces a $d\bar{d}$ pair in the final state, has an interesting relation to the $\pi^-\Delta^{++}$ reaction producing a $u\bar{u}$ pair. Clebsch-Gordan coefficients predict cross section ratios of the two reactions in the case of the excitation of isospin 1/2(N^*) and 3/2(Δ^*). If a nucleon resonance is excited in the intermediate state, the

cross section ratio $d\sigma(\pi^+\Delta^0)/d\sigma(\pi^-\Delta^{++})$ becomes 1/3. In case a Δ resonance is excited, the cross section ratio becomes 4/3. In the energy regions relating to nucleon resonances, SAPHIR measured the total cross sections for both the reactions for photon energies from the threshold to 2.6 GeV [32]. Although SAPHIR also measured the differential cross sections for the $\pi^-\Delta^{++}$ reaction, those for the $\pi^+\Delta^0$ reaction were not measured because of low statistics.

Figure 4 shows the missing mass of the $\gamma p \to \pi^+ X$ and $\gamma p \to \pi^- X$ reactions. Since the LEPS spectrometer [4] has the same acceptance for positive and negative charged particles, precise comparison between the $\pi^+ X$ and $\pi^- X$ reactions is possible.

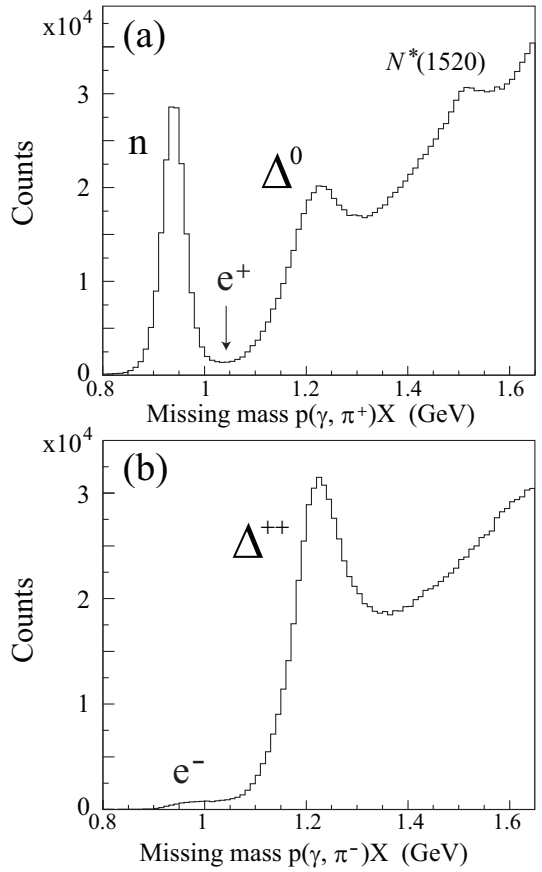

Figure 4. Missing mass of the (a) $\gamma p \to \pi^+ X$ and (b) $\gamma p \to \pi^- X$ reactions for 0.7< $\cos\theta_{cm}$ <1 and E_γ=1.5-2.95 GeV.

In the $\pi^+ X$ reaction, the neutron peak and $\Delta^0(1232)$ bump are clearly observed. The events between the peak and bump are due to positron mis-identification in the π^+ sample. The positron events contaminate the π^+ sample at very forward angles only. The yield of the $\pi^+\Delta^0$ reaction was obtained by fitting to the missing mass with a relativistic Breit-Wigner shape [33, 34] for the Δ^0 bump. The background under the bump was fitted with curves for 2π, 3π, ρ, and positron events which were reproduced by GEANT simulations [35]. The shapes of the curves were fixed and the heights of the curves were free parameters to fit to the background. The number of the $\pi^+\Delta^0$ events was about 190 k.

In the $\pi^- X$ reaction, the $\Delta^{++}(1232)$ bump is dominantly observed. The events around 1.0 GeV are due to mis-identification of electrons in the π^- sample. The electron events exist at very forward angles only. The yield of the $\pi^-\Delta^{++}$ reaction was obtained by fitting to the missing mass [21] with a similar method to the $\pi^+\Delta^0$ reaction. The number of the $\pi^-\Delta^{++}$ events was about 400 k which was roughly 2 times larger than that of the $\pi^+\Delta^0$ events.

Figure 5 shows preliminary cross section ratios $d\sigma(\pi^+\Delta^0)/d\sigma(\pi^-\Delta^{++})$ as a function of the photon beam energy. It is interesting that the ratios are found to be close to 1/3 for 0.966< $\cos\theta_{cm}$ <1 for all the energies. The ratio of 1/3 is expected from the exchange of isospin=1 in the t channel. The ρ-meson and π-meson are good candidates for the exchanged particle. This result means that the Clebsch-Gordan coefficients work excellently and our knowledge on the t-channel hadron photoproduction is correct in this kinematical region. The cross section ratios become larger than 1/3 for 0.9< $\cos\theta_{cm}$ <0.966 and E_γ >2.2 GeV. The ratios become close to 1 for 0.7< $\cos\theta_{cm}$ <0.9 and E_γ >2.4 GeV. One explanation for the ratios close to 1 might be a contribution from Δ resonances. If the Δ resonances are excited in the s channel, the ratios become 4/3. Another explanation is the exchange of isospin=2 exotic meson, which is expected to give a ratio of 2, in the t channel. Interference between the ρ-meson and π-meson exchanges might cause larger ratios. Advanced theoretical calculations introducing nucleon resonances and exotic meson exchanges are needed to understand the present results.

4 Summary

We have precisely studied photoproduction reactions which produce $u\bar{u}$, $d\bar{d}$, and $s\bar{s}$ quark-antiquark pairs for the first time. The differential cross sections for the $\gamma p \to \pi^-\Delta^{++}$, $\pi^+ n$, and $K^+\Lambda(K^+\Sigma^0)$ reactions are forward-peaking, which suggests the dominance of t-channel reaction mechanisms. The $\pi^+ n$ and $K^+\Lambda(K^+\Sigma^0)$ reactions have positive photon beam asymmetries obtained by using linearly polarized photon beams. The $\pi^-\Delta^{++}$ reaction is found to have negative asymmetries which are different from other pseudoscalar meson photoproduction reactions. We obtained preliminary differential cross sections for the $\gamma p \to \pi^+\Delta^0$ reaction producing a $d\bar{d}$ quark-antiquark pair. Precise comparison among these various quark-antiquark pair productions plays an important role in obtaining unified understanding of reaction mechanisms including nucleon and Δ resonances excited in the intermediate state.

We are developing a polarized HD target [36–39] for near future experiments at SPring-8/LEPS. The highest polarization for the proton target was 44±1% and the longest relaxation time was 8±2 months. Skills for the transportation of the polarized HD target from Osaka University to SPring-8 are needed before starting physics experiments. We are also developing a large acceptance spectrometer for charged particles at SPring-8/LEPS2. Introducing the polarized HD target to these experiments is

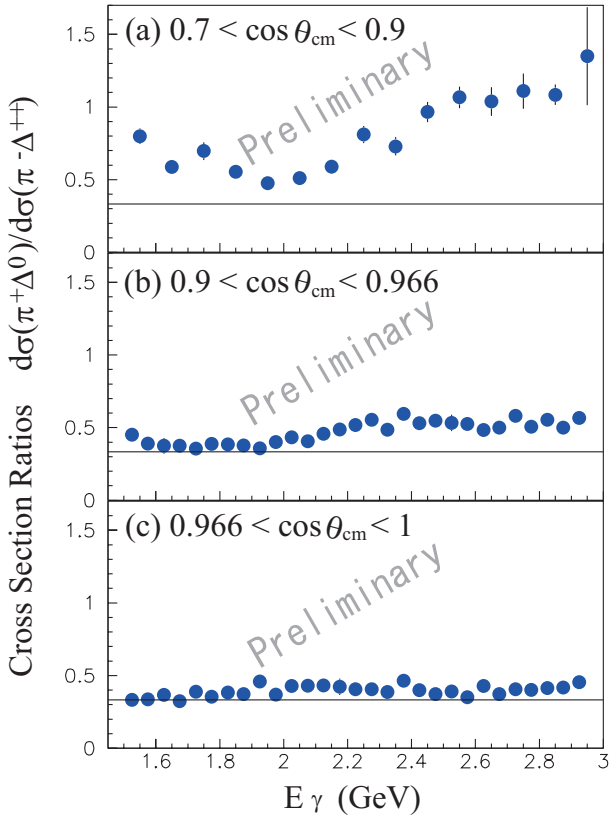

Figure 5. Preliminary cross section ratios $d\sigma(\pi^+\Delta^0)/d\sigma(\pi^-\Delta^{++})$ for (a) $0.7< \cos\theta_{cm} <0.9$, (b) $0.9< \cos\theta_{cm} <0.966$, and (c) $0.966< \cos\theta_{cm} <1$.

expected to advance the study of the nucleon and Δ resonances.

5 Acknowledgement

The authors gratefully acknowledge the staff of the SPring-8 facility for the support with excellent experimental conditions. The experiments were performed at the BL33LEP of SPring-8 with the approval of the Japan Synchrotron Radiation Research Institute (JASRI) as a contract beam line (Proposal No. BL33LEP/6001). This research was supported in part by the Ministry of Education, Science, Sports and Culture of Japan, the Ministry of Science and Technology of Taiwan, the National Research Foundation of Korea, and the U.S. National Science Foundation.

References

[1] Simon Capstick and Winston Roberts, Phys. Rev. D **49**, 4570 (1994)
[2] Simon Capstick and W. Roberts, Phys. Rev. D **58**, 074011 (1998)
[3] N. Muramatsu et al., Nucl. Instrum. Methods. Phys. Res. Sect. A **737**, 184 (2014)
[4] T. Nakano et al., Nucl. Phys. A **684**, 71 (2001)
[5] T. Mibe et al., Phys. Rev. Lett. **95**, 182001 (2005)
[6] T. Ishikawa et al., Phys. Lett. B **608**, 215 (2005)
[7] W. C. Chang et al., Phys. Lett. B **658**, 209 (2008)
[8] W. C. Chang et al., Phys. Rev. C **82**, 015205 (2010)
[9] W. C. Chang et al., Phys. Lett. B **684**, 6 (2010)
[10] S. Y. Ryu et al., Phys. Rev. Lett. **116**, 232001 (2016)
[11] W. C. Mizutani et al., Phys. Rev. C **96**, 062201(R) (2017)
[12] R. G. T. Zegers et al., Phys. Rev. Lett. **91**, 092001 (2003)
[13] M. Sumihama et al., Phys. Rev. C **73**, 035214 (2006)
[14] H. Kohri et al., Phys. Rev. Lett. **97**, 082003 (2006)
[15] M. Niiyama et al., Phys. Rev. C **78**, 035202 (2008)
[16] K. Hicks et al., Phys. Rev. Lett. **102**, 012501 (2009)
[17] N. Muramatsu et al., Phys. Rev. Lett. **103**, 012001 (2009)
[18] H. Kohri et al., Phys. Rev. Lett. **104**, 172001 (2010)
[19] A. O. Tokiyasu et al., Phys. Lett. B **728**, 616 (2014)
[20] S. H. Hwang et al., Phys. Rev. Lett. **108**, 092001 (2012)
[21] H. Kohri et al., Phys. Rev. Lett. **120**, 202004 (2018)
[22] H. Kohri et al., Phys. Rev. C **97**, 015205 (2018)
[23] S. H. Shiu et al., Phys. Rev. C **97**, 015208 (2018)
[24] G. Boschhorn et al., Phys. Rev. Lett. **17**, 1027 (1966)
[25] G. Boschhorn et al., Phys. Rev. Lett. **18**, 571 (1967)
[26] M. Dugger et al., Phys. Rev. C **79**, 065206 (2009)
[27] M. Guidal, J.-M. Laget, and M. Vanderhaeghen, Nucl. Phys. A **627**, 645 (1997)
[28] M. Dugger et al., Phys. Rev. C **88**, 065203 (2013)
[29] N. Sparks et al., Phys. Rev. C **81**, 065210 (2010)
[30] D. Elsner et al., Eur. Phys. J. A **33**, 147 (2007)
[31] P. Collins et al., Phys. Lett. B **771**, 213 (2017)
[32] C. Wu et al., Eur. Phys. J. A **23**, 317 (2005)
[33] J. D. Jackson, Nuovo Cimento **34**, 1644 (1964)
[34] A. M. Boyarski et al., Phys. Rev. Lett. **22**, 148 (1969)
[35] H. Kohri for LEPS collaboration, Few-Body Syst **59**, 88 (2018)
[36] H. Kohri, Int. Jour. of Mod. Phys. E **19**, 903 (2010)
[37] T. Ohta et al., Nucl. Instrum. Methods. Phys. Res. Sect. A **633**, 46 (2011)
[38] T. Ohta et al., Nucl. Instrum. Methods. Phys. Res. Sect. A **640**, 241 (2011)
[39] T. Ohta et al., Nucl. Instrum. Methods. Phys. Res. Sect. A **664**, 347 (2012)