Overview of hadron photoproduction experiments in SPring-8 LEPS2 project

Norihito Muramatsu[1,*]

[1]Research Center for Electron Photon Science, Tohoku University, Sendai, Miyagi 982-0826, Japan

Abstract. An experimental project to study hadron properties through photoproduction reactions is carried out in SPring-8 LEPS2 beamline. As an overview of this project, recent physics achievements and prospects on light baryon spectroscopy, exotic hadrons / bound states, and the origin of hadron mass are discussed with the description of experimental setups.

1 LEPS2 project

A GeV photon beam is useful because its polarization is available to investigate the nature of hadrons. For instance, the spin information of intermediate or final states in the *s*- and *t*-channels of hadron photoproduction processes can be extracted by using a linearly polarized photon beam and examining the asymmetries of particle emission angles relative to the polarization vector. Such a photon beam is usually produced via laser Compton scattering or coherent bremsstrahlung in a high-energy electron accelerator facility, and the former method provides higher linear polarization at higher photon beam energies. Currently, only the LEPS2 beamline in SPring-8 adopts laser Compton scattering for hadron photoproduction experiments, and its high linear polarization is unique over the world for the photon beam energies from 1.9 to 3 GeV.

The LEPS2 beamline was constructed as a second laser-Compton-scattering beamline of SPring-8. Details of the beamline structure and properties are described in Ref. [1]. In the normal operation of this beamline, the photon beam energy reaches a maximum of 2.4 GeV, and individual photon energies are measured in the range above 1.3 GeV by using "Tagger", which detects recoil electrons. A tagged photon intensity was 1–3M cps with multiple laser injection. When the laser light is fully linear-polarized, the photon beam has high linear polarization in the range from 40% (at 1.3 GeV) to 94% (at 2.4 GeV).

In the project using the LEPS2 beamline, two large-acceptance detector setups have been operated alternately inside an experimental building located most downstream. As an initial program, BGOegg experiment was carried out by using an electromagnetic calorimeter that consists of 1320 $Bi_4Ge_3O_{12}$ (BGO) crystals surrounding a fixed target of liquid hydrogen or carbon in the polar angle range of 24–144 degrees, as shown in Fig. 1(a). This calorimeter shows the world's best mass resolutions for neutral hadrons decaying into γs (e.g., σ = 6.7 MeV/c^2 for π^0 decaying into $\gamma\gamma$ when using a 20 mm thick target) at low energies. The other detector setup that contains a charged-particle spectrometer inside a 0.9 T solenoid magnet (Fig. 1(b)) has been constructed downstream of the BGOegg experimental

*e-mail: mura@lns.tohoku.ac.jp

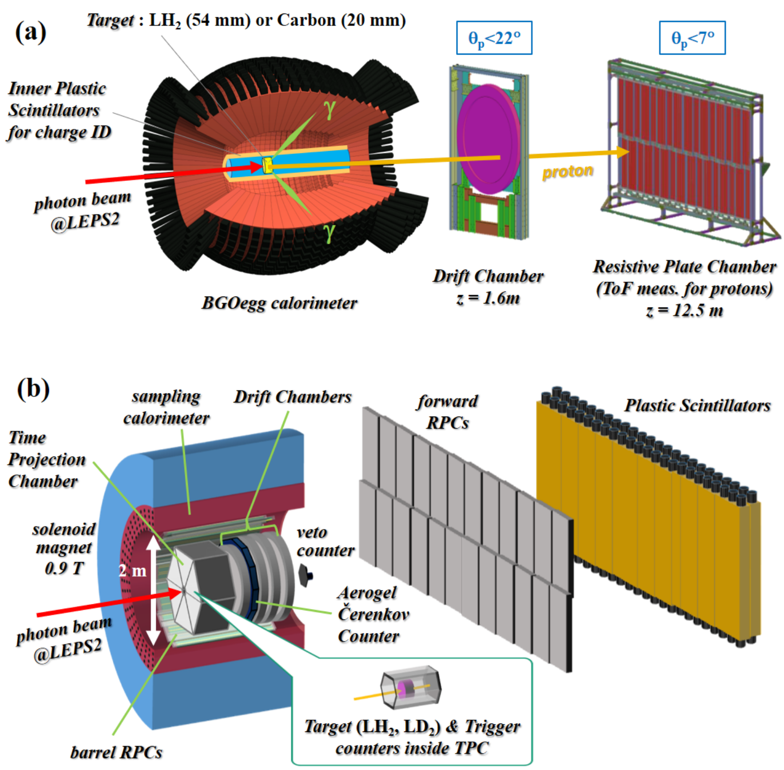

Figure 1. Two detector setups for hadron photoproduction experiments in SPring-8 LEPS2 project. (a) and (b) show the detector systems for BGOegg experiment and LEPS2/Solenoid experiment, respectively.

area. Physics data collection with this setup (LEPS2/Solenoid experiment) started from 2021 by using a liquid hydrogen or deuterium target. The LEPS2 project treats wide subjects including light baryon spectroscopy, exotic hadrons / bound states, and the origin of hadron mass by using the two detector setups and a linearly polarized photon beam. The following sections overview individual physics subjects.

2 Light baryon spectroscopy

Meson photoproduction experiments are suitable to perform light baryon spectroscopy by exciting a target nucleon to a higher nucleon or Δ resonance (N^* or Δ^*) in the s-channel. Systematic data from such experiments are now the main input for partial wave analyses (PWAs) to establish baryon mass spectra. There are still unobserved states in comparison with the predictions by constituent quark models and lattice QCD calculations in the mass range above around 2 GeV, where resonances having large widths are overlapped with each other. Differential cross sections and polarization observables of an exclusive photoproduction reaction are sensitive to the absolute values and interferences of spin amplitudes (e.g., CGLN amplitudes) containing resonance contributions, respectively. Therefore, a simultaneous measurement of them is important to increase the information for amplitude decomposition.

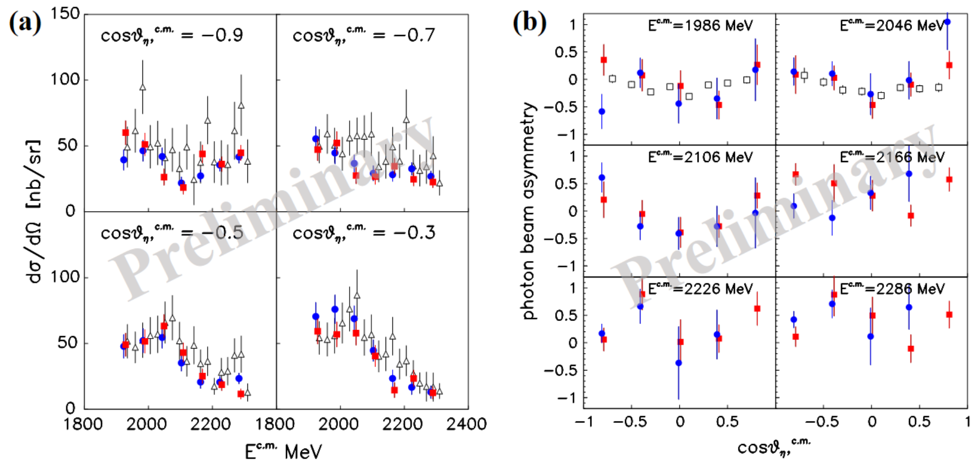

Figure 2. Preliminary results for (a) differential cross sections and (b) photon beam asymmetries of the reaction $\gamma p \to \eta' p$, measured by BGOegg experiment. Red closed squares and blue closed circles come from the analyses of $\eta' \to \gamma\gamma$ and $\eta' \to \eta\pi^0\pi^0 \to 6\gamma$ decays, respectively. Black open triangles and squares represent the measurements by CBELSA/TAPS [5] and CLAS [6] collaborations, respectively.

The reactions $\gamma p \to \pi^0 p$ [2], ηp [3], and ωp [4] have been analyzed in the BGOegg experiment. The final-state mesons were identified from the decays $\pi^0 \to \gamma\gamma$, $\eta \to \gamma\gamma$, and $\omega \to \pi^0\gamma \to 3\gamma$, respectively. Individual reactions were selected by a kinematic fit with constraints of the four-momentum conservation and the π^0 or η mass. The difference of final states is helpful to get extra information about resonances. For example, photoproduction of the η or ω meson, whose isospin is zero, is contributed only from N^*s. The η photoproduction has advantage in investigating the coupling of N^*s with an $s\bar{s}$ component.

The BGOegg results of differential cross sections and polarization observables (photon beam asymmetries and spin density matrix elements) for the above reactions are detailed in Refs. [2–4]. The new data of differential cross sections have the highest precision at extremely backward meson angles among the existing experimental results. Particularly, the total-energy dependence of differential cross sections in η photoproduction shows a bump structure at 2.0–2.3 GeV in the extremely backward region, possibly indicating high-spin N^*s which couple with $s\bar{s}$. For all the reaction modes, photon beam asymmetries measured over a wide angular range by using a linearly polarized photon beam are the first data at total energies above 2.1 GeV. In the π^0 photoproduction, a dip structure around $\cos\theta_{\pi^0}^{c.m.} \sim -0.8$ appears only at higher energies, suggesting the existence of a high spin resonance.

Photoproduction of η' mesons, which have a large mass, is important to explore higher mass resonances, but experimental data are scarce. Figures 2(a) and 2(b) are the preliminary BGOegg results of differential cross sections and photon beam asymmetries, respectively. The η' meson was identified in the two decay modes of $\gamma\gamma$ and $\eta\pi^0\pi^0$ (6γ). Results for the two decay modes are consistent with each other, and they statistically match with the existing experimental data in the overlapped kinematical region. Differential cross sections in the most backward η'-angle bin behave differently from those in other angular regions and show an enhancement at higher energies, as seen in the η photoproduction. The angular dependence of photon beam asymmetries which are newly measured at the higher energies differ from the behavior at the lower energies, providing new constraints for resonance contributions.

3 Exotic hadrons / bound states

The scalar meson $f_0(980)$ is historically considered as a candidate of exotic states like a $K\bar{K}$ molecule and a tetraquark. The differential cross sections and photon beam asymmetries of its photoproduction may be sensitive to the internal quark structure [7]. In the BGOegg experiment, the reaction $\gamma p \to \pi^0\pi^0 p \to 4\gamma p$ was analyzed to observe this meson in the $f_0(980) \to \pi^0\pi^0$ decay mode [8]. As a result, a clear peak was identified in the $\pi^0\pi^0$ invariant mass distribution simply after removing a large contribution from $\pi^0\Delta$ photoproduction. Here, the $\pi^0\pi^0$ invariant mass spectrum is not influenced from the photoproduction of ρ mesons, which predominantly decay into $\pi^+\pi^-$. In two total-energy regions (1898–2110 and 2110–2320 MeV), the first measurements were done for the differential cross section of $\gamma p \to f_0(980)p \to \pi^0\pi^0 p$ and the photon beam asymmetry of $\gamma p \to f_0(980)p$.

The measured photon beam asymmetries decrease to around −0.3 at the higher energies, whereas they are about zero at the lower energies. The negative sign of photon beam asymmetries in scalar meson photoproduction indicates t-channel exchange of a vector meson, which is assumed as a diagram in the theoretical calculation of Ref. [7]. Differential cross sections of the reaction $\gamma p \to f_0(980)p \to \pi^0\pi^0 p$ in the higher energy region were measured as shown in Fig. 3. Increase of differential cross sections at small $|-t|$, corresponding to forward meson production, was seen as expected for a t-channel process. Furthermore, this result can be compared with the theoretical prediction in Ref. [7], which argues that differential cross sections with "No Structure" model should be much larger than those with "Kaon Loop" model. The measured differential cross sections $\frac{d\sigma}{dt}$ were 122–156 nb/GeV^2 at $|-t| < 1$ GeV^2, indicating the values closer to the prediction with "No Structure" model.

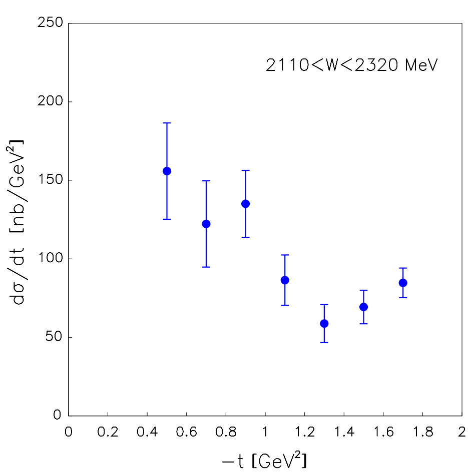

Figure 3. Differential cross sections $\frac{d\sigma}{dt}$ of the reaction $\gamma p \to f_0(980)p \to \pi^0\pi^0 p$ at total energies from 2110 to 2320 MeV.

In the LEPS2/Solenoid experiment, an exotic hadronic bound state of $K^- pp$, which is extensively discussed in connection with the equation of state in neutron stars, is searched for by the reaction $\gamma d \to K^0_S(K^- pp)_{B.S.} \to K^0_S \Lambda p$ [9]. A mass resolution of 17 MeV is expected for the Λp invariant mass which will be reconstructed from the measurement at the time projection chamber. If this state exists with an enough cross section, the LEPS2/Solenoid experiment can measure the binding energy, whose experimental values differ from each other in the range of 40–120 MeV among existing data [10–13].

4 Origin of hadron mass

Change of vacuum properties due to the spontaneous breaking of chiral symmetry is widely considered as the origin of hadron mass. To obtain an evidence for this mass generation mechanism, the BGOegg experiment focuses on photoproduction of η' mesons by using a nuclear target, which provides a high-density environment possibly causing partial restoration of the chiral symmetry or reduction of the η' mass. The predicted amount of η' mass reduction at the nuclear density varies from 40 to 150 MeV depending on theoretical models [14–16]. Thus, experimental measurement of in-medium η' mass is important to provide constraints to effective Lagrangians used in those models. In addition, the study of η' mass may shed light on the relation between the spontaneous breaking of chiral symmetry and the $U_A(1)$ quantum anomaly [17].

In the BGOegg phase-1 experiment, in-medium η' mass was studied by adopting two analysis methods for the data collected with a carbon target: Firstly, η' bound nuclei, whose binding energy arose from the η' mass reduction, were searched for in the reaction $\gamma +^{12} C \rightarrow (\eta' \ ^{11}B)_{B.S.} + p$ with the detection of an extremely forward-going proton [18]. Simultaneously, a nuclear absorption signal of the bound η' ($\eta' p \rightarrow \eta p$) was tagged, for the first time, by detecting the back-to-back emission of an η meson decaying into $\gamma\gamma$ and a slow proton in the BGOegg calorimeter. However, bound-state signals were not observed below the threshold of quasi-free η' production in the excitation energy spectrum, which was calculated from the missing mass of a forward proton. An experimental upper limit of the differential cross section was evaluated to be 2.2 nb/sr, indicating the η' mass reduction much less than 100 MeV.

Secondly, direct measurement of the in-medium η' mass was performed by detecting $\eta' \rightarrow \gamma\gamma$ decays in the BGOegg calorimeter [19]. A $\gamma\gamma$ invariant mass spectrum was measured after selecting low $\gamma\gamma$ momentum events in the data collected with a carbon target, and the existence of mass reduction signals was examined in the region below a quasi-free η' peak. This examination was done in several ways: (1) by counting the amount of excess with a background fit to the mass range except for the signal search region, and (2) by performing χ^2 difference tests which compare two fits including or excluding a signal component in a fitting function. Preliminary results of all the cases indicate 3–4σ enhancement of possible signals, while the excess above a background fit is not significant both in the higher $\gamma\gamma$ momentum sample of the carbon target data and the lower $\gamma\gamma$ momentum sample of the liquid hydrogen target data. One of the χ^2 difference tests shows a hint of the mass reduction around 60 MeV, which is consistent with the result of the η' bound nuclei search. This observation is being confirmed by increasing the sample statistics twice with unanalyzed data.

The BGOegg phase-2 experiment is now on-going to clarify the phase-1 result of direct measurement with higher statistics and smaller systematic uncertainties. A copper target, whose nuclear radius is 1.8 times larger than that of carbon, will be used with an effective thickness increased from 0.1 to 0.5 radiation lengths. A photon beam intensity is also being increased to about 5M cps by introducing a new pulsed laser. Multi-meson backgrounds, mainly coming from the reaction $\gamma p \rightarrow \pi^0\pi^0 p \rightarrow 4\gamma p$, are significantly reduced by covering a forward acceptance hole of the BGOegg calorimeter with another calorimeter system. New data collection will start in 2024.

5 Summary

In SPring-8 LEPS2 beamline, a tagged photon beam of 1.3–2.4 GeV is utilized for hadron photoproduction experiments with two different setups: the BGOegg experiment and the LEPS2/Solenoid experiment. High linear polarization of the photon beam is unique for the energy range from 1.9 to a few GeV, and useful to measure polarization observables for obtaining the spin information of intermediate- or final-state hadrons. Differential cross sections, photon beam asymmetries, and spin density matrix elements were measured by the BGOegg experiment for the studies of N^* or Δ^* resonances in π^0 / η / ω / η' photoproduction and an exotic hadron structure in $f_0(980)$ photoproduction. The BGOegg experiment also explored in-medium mass reduction of η' mesons to study the origin of hadron mass. Based on the results obtained from the η' bound nuclei search and the direct mass measurement using $\eta' \to \gamma\gamma$ decays, the phase-2 experiment has started to collect new data with higher statistics and lower systematic uncertainties. The LEPS2/Solenoid experiment can cover wide subjects to investigate hadron properties. Currently, an analysis to search for an exotic $K^- pp$ bound state is extensively carried out.

References

[1] N. Muramatsu, M. Yosoi, T. Yorita, Y. Ohashi *et al.*, Nucl. Instrum. Meth. Phys. Res. A **1033**, 166677 (2022).

[2] N. Muramatsu *et al.* (LEPS2/BGOegg Collaboration), Phys. Rev. C **100**, 055202 (2019).

[3] T. Hashimoto, T. Nam, N. Muramatsu *et al.* (LEPS2/BGOegg Collaboration), Phys. Rev. C **106**, 035201 (2022).

[4] N. Muramatsu *et al.* (LEPS2/BGOegg Collaboration), Phys. Rev. C **102**, 025201 (2020).

[5] V. Crede, A. McVeigh *et al.* (CBELSA/TAPS Collaboration), Phys. Rev. C **80**, 055202 (2009).

[6] P. Collins, B.G. Ritchie, M. Dugger *et al.*, Phys. Lett. B **771**, 213 (2017).

[7] A. Donnachie and Yu. S. Kalashnikova, Phys. Rev. C **93**, 025203 (2016).

[8] N. Muramatsu, S.K. Wang, Q.H. He *et al.* (LEPS2/BGOegg Collaboration), Phys. Rev. C **107**, L042201 (2023).

[9] R. Kobayakawa, Private communication.

[10] S. Ajimura *et al.* (J-PARC E15 collaboration), Phys. Lett. B **789**, 620 (2019).

[11] Y. Ichikawa, T. Nagae, H. Fujioka *et al.*, Prog. Theor. Exp. Phys. **2015-2**, 021D01 (2015).

[12] T. Yamazaki, M. Maggiora, P. Kienle, K. Suzuki *et al.*, Phys. Rev. Lett. **104**, 132502 (2010).

[13] M. Agnello *et al.* (FINUDA Collaboration), Phys. Rev. Lett. **94**, 212303 (2005).

[14] H. Nagahiro. M. Takizawa, and S. Hirenzaki, Phys. Rev. C **74**, 045203 (2006).

[15] S. Sakai and D. Jido, Phys. Rev. C **88**, 064906 (2013).

[16] S.D. Bass and A.W. Thomas, Phys. Lett. B **634**, 368 (2006).

[17] S. Kono, D. Jido, Y. Kuroda, and M. Harada, Prog. Theor. Exp. Phys. **2021-9**, 093D02 (2021).

[18] N. Tomida, N. Muramatsu, M. Niiyama *et al.* (LEPS2/BGOegg Collaboration), Phys. Rev. Lett. **124**, 202501 (2020).

[19] Y. Matsumura, Doctoral Thesis (Tohoku University, 2021).