# Recent results from LEPS2/BGOegg on light baryon spectroscopy

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**Summary.** — Light baryon spectroscopy is conducted by BGOegg experiment in SPring-8 LEPS2 beamline, which uniquely provides a highly linear-polarized photon beam up to 2.4 GeV. Differential cross sections, photon beam asymmetries, and spin density matrix elements are measured for photoproduction of the $\pi^0$, $\eta$, $\omega$, or $\eta'$ meson. New results contain the first precise data of differential cross sections at extremely backward meson angles and polarization observables at $E_\gamma > 1.9$ GeV.

## 1. – Introduction

Photoproduction of light mesons is suitable for the spectroscopy of nucleon and $\Delta$ resonances ($N^*$s and $\Delta^*$s), which are produced in the $s$-channel. Now the main input for partial wave analyses (PWAs) to establish those baryon mass spectra comes from systematic data of the meson photoproduction experiments instead of the old $\pi N$ scattering data [1]. Not only differential cross sections but also various polarization observables are measurable for photoproduction reactions because a photon beam can be polarized. The polarization observables are useful to obtain the spin information of resonances. In addition, a type of the final-state meson is sensitive to the nature of intermediate resonances. It is known that there are many missing resonances in the mass range above around 2 GeV when existing experimental data are compared with the spectra predicted by constituent quark models and lattice QCD calculations. New and high-statistics photoproduction data with various polarization combinations and final states are still needed to reveal the light baryon spectra.

Spin amplitudes of a photoproduction reaction are described by partial waves containing the contribution of baryon resonances. In the case of pseudoscalar meson photoproduction, it has been proposed to solve four spin amplitudes by four or five observables, including differential cross sections and polarization observables (so-called "complete sets" in the truncated PWA) [2]. The proposed sets of observables usually contain the photon beam asymmetry, which is one of polarization observables using a linearly polarized photon beam, because the production of such a beam is relatively easy with high intensity. The LEPS2 beamline in SPring-8 adopts laser Compton scattering for the production of a photon beam and uniquely provides high linear polarization at a few GeV energies. This feature has not been achieved in coherent bremsstrahlung facilities for the range from 1.9 GeV to the GlueX energy ($\approx$ 9 GeV). The photon beam asymmetry of an exclusive reaction represents the interference of spin amplitudes, while the differential cross section shows the sum of their squares. The high linear polarization in the LEPS2 beamline is favorable to decompose overlapped high-spin resonances with large widths.

## 2. – Light baryon spectroscopy in BGOegg experiment

Details of the LEPS2 beamline and facilities are described in Ref. [3]. Photons are tagged in the energy range from 1.3 to 2.4 GeV and delivered to the experimental building located most downstream with an intensity of 1–3 $\times 10^6$ cps. The photon beam has high linear-polarization from 40% (at 1.3 GeV) to 94% (at 2.4 GeV) when injecting fully polarized laser light into the electron storage ring of SPring-8.

In the experimental building, BGOegg experiment was carried out by setting up a large-acceptance electromagnetic calorimeter that consists of 1320 $Bi_4Ge_3O_{12}$ (BGO) crystals surrounding a fixed target of 54 mm thick liquid hydrogen in the polar angle range of 24–144 degrees. At low energies, this calorimeter shows the world's best performance, achieving mass resolutions of 6.7 and 14.4 MeV for $2\gamma$ decays of $\pi^0$ and $\eta$ mesons, respectively, when using a thinner target. Charge identification of calorimeter hits was done by plastic scintillators aligned cylindrically inside the calorimeter. The forward acceptance at polar angles smaller than 22 degrees are covered by a planar drift chamber (DC) and a wall of resistive plate chambers (RPCs) for charged-particle detection.

So far, the reactions $\gamma p \to \pi^0 p$ [4], $\eta p$ [5], and $\omega p$ [6] 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, by using the four-momenta of all $\gamma$s measured at the calorimeter. In addition, a proton was detected at either of the calorimeter or the planar DC to measure its direction. A kinematic fit was applied to select signal events with constraints of the four-momentum conservation between the initial and final states while forcing the invariant mass of a $2\gamma$ combination to the nominal value for $\pi^0$ or $\eta$.

After counting signals, differential cross sections and photon beam asymmetries of these reactions were obtained with appropriate binning for meson angles $-1 < \cos\theta^{c.m.} < 0.6$ and total energies $1.82 < W < 2.32$ GeV. The BGOegg experiment ensures reliability by detecting all the final-state particles without a missing mass technique, particularly at backward meson angles. For $\gamma p \to \omega p$, spin density matrix elements were also measured to define an increased number of spin amplitudes in the case of vector meson photoproduction. Recently, new results for $\eta'$ photoproduction are being extracted from the BGOegg data, as discussed later. Hereafter, this article concentrates on the results for pseudoscalar meson photoproduction.

## 3. – $\pi^0$ and $\eta$ photoproduction

The isospin of $\pi^0$ is one, so that both $N^*$s and $\Delta^*$s contribute to the $\pi^0$ photoproduction process. High precision data have been obtained worldwide thanks to the relatively large cross section, but there is a slight discrepancy among the previous data of differential cross sections at $\cos\theta^{c.m.}_{\pi^0} < -0.5$. Photon beam asymmetries measured over wide $\pi^0$ angles do not exist at the photon beam energies $E_\gamma > 1.9$ GeV. The BGOegg experiment collected about 650K events of the $\pi^0$ photoproduction process for new measurements.

Differential cross sections and photon beam asymmetries obtained by the BGOegg experiment are detailed in Ref. [4]. The measured differential cross sections were closer

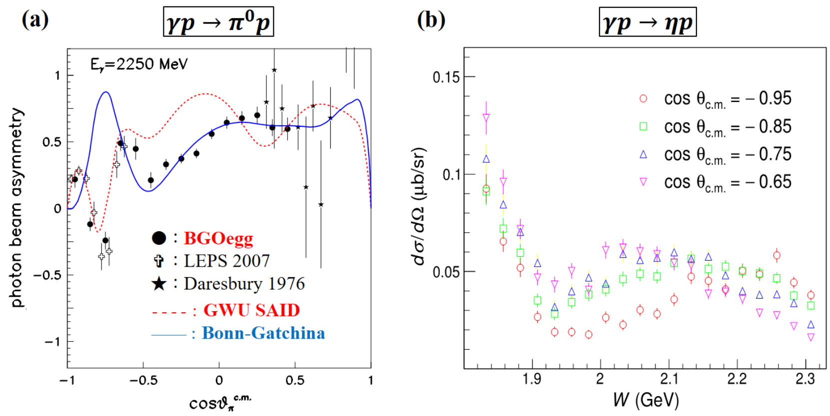


Fig. 1. – BGOegg results for (a) photon beam asymmetries of $\gamma p \to \pi^0 p$ at $2.2 < E_\gamma < 2.3$ GeV and (b) differential cross sections of $\gamma p \to \eta p$ at $\cos\theta_\eta^{c.m.} < -0.6$.

to the CLAS, Graal, and LEPS results at backward $\pi^0$ angles. The $\pi^0$-angle dependence of differential cross sections shows strongly energy-dependent enhancements in backward and middle angle regions, which are sensitive to the existence of baryon resonances. The BGOegg result of photon beam asymmetries shows the same angular dependence as the other experimental data at $E_\gamma < 1.9$ GeV, while its absolute values are slightly smaller than those with a coherent bremsstrahlung beam. None of existing PWA calculations reproduce the angular dependence of photon beam asymmetries at higher energies, where precise and wide angular data have been missing. Only at higher energies ($2.1 < E_\gamma <$ 2.4 GeV), a dip structure around $\cos\theta_{\pi^0}^{c.m.} \approx -0.8$ appears, suggesting the contribution of a high spin resonance with $J^P = \frac{9}{2}^+$. (See Fig. 1(a).)

For $\eta$ photoproduction, only $N^*$s can be produced in the $s$-channel because the isospin of $\eta$ is zero. The $\eta$ photoproduction has advantage in investigating the coupling of $N^*$s with a $s\bar{s}$ component. The differential cross sections of previous experiments were largely inconsistent with each other at $\cos\theta_\eta^{c.m.} < -0.2$. Photon beam asymmetries had not been measured even partly at $W > 2.1$ GeV. About 55K signal events were selected for the measurement of these observables in the BGOegg experiment [5]. The obtained result was partly confirmed by an independent analysis which additionally measured the proton momentum using the RPC wall to get full kinematic information.

The new data of differential cross sections have the highest precision at extremely backward $\eta$ angles among the existing experimental results. The BGOegg result was consistent with the CLAS data at $\cos\theta_\eta^{c.m.} > -0.8$, but not with the CBELSA/TAPS and LEPS data in the backward $\eta$-angle region. The consistency between the BGOegg and CLAS results becomes worse at $\cos\theta_\eta^{c.m.} = -0.85$, which is the acceptance boundary of the CLAS measurement. The total-energy dependence of differential cross sections shows a bump structure at 2.0–2.3 GeV when the $\eta$ meson is detected in the extremely backward region. (See Fig. 1(b).) The shape and peak position of the bump structure strongly depend on $\cos\theta_\eta^{c.m.}$, and it is difficult to explain this behavior only by introducing $N(1895)\frac{1}{2}^-$, which also decays into $\eta' p$. There may be additional contributions from high-spin $N^*$s coupling with $s\bar{s}$. The new precise data of photon beam asymmetries do not match existing PWA calculations at higher energies and thus requires an improved PWA solution for high-mass $N^*$ contributions.

## 4. – $\eta'$ photoproduction

Similar to the case of $\eta$ photoproduction, only $N^*$s contribute to photoproduction of the $\eta'$ meson with indication of their coupling to $s\bar{s}$. Because the mass of the $\eta'$ meson is very large, its photoproduction is important to explore higher mass resonances. However, the experimental data of $\eta'$ photoproduction are still scarce, particularly for polarization observables. In the BGOegg experiment, photoproduced $\eta'$ mesons were identified in the two decay modes of $\gamma\gamma$ and $\eta\pi^0\pi^0$ ($6\gamma$). Kinematic fits were done for signal selection, producing the sample of a few thousand events for each decay mode.

Figure 2(a) shows a preliminary result of differential cross sections. Results from the two decay modes are consistent with each other, and they statistically match the CLAS [7] and CBELSA/TAPS [8] results in the overlapped kinematical region. High precision measurement was newly achieved at extremely backward $\eta'$ angles. If the differential cross sections of the most backward angle bin are plotted as a function of the total energy, a bump structure at higher energies appears as observed in $\eta$ photoproduction.

A preliminary result of photon beam asymmetries was obtained as shown in Fig. 2(b). Two results from the different decay modes are consistent with each other, although the lowest energy bin is affected by large statistical uncertainties. The BGOegg results statistically agree with the CLAS [9] and Graal [10] data at $W < 2.078$ GeV. The angular dependence of photon beam asymmetries that are newly measured at the higher energies differ from the behavior at the lower energies. A variety of angular dependence patterns are predicted because nucleon resonance contributions and their coupling to $\eta' p$ are not well fixed yet at higher energies [11]. For providing tight constraints to

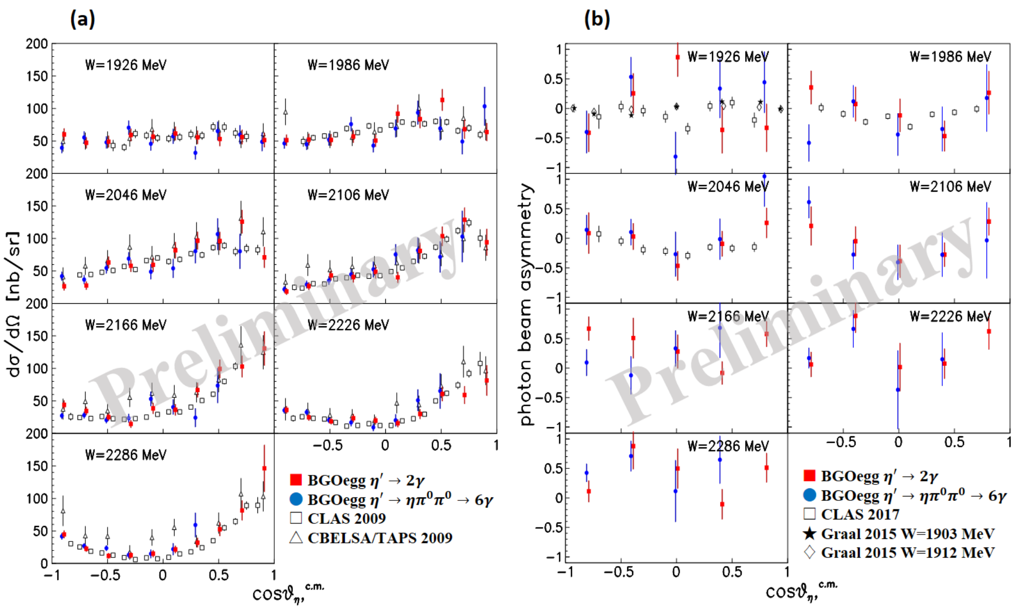


Fig. 2. – (a) Differential cross sections and (b) photon beam asymmetries of $\gamma p \to \eta' p$.

theoretical calculations, the size of data samples in the BGOegg experiment is being doubled by combining unanalyzed data.

## 5. – Summary and prospects

In the BGOegg experiment, meson photoproduction off the proton is intensively studied for the spectroscopy of light baryon resonances. This experiment is unique due to utilizing a highly linear-polarized photon beam at $1.3 < E_\gamma < 2.4$ ($1.82 < W < 2.32$) GeV. Polarization observables obtained with such a beam are new at $E_\gamma > 1.9$ GeV, providing the spin information of intermediate resonances. In addition, precise data are newly given over a wide meson-angle range, particularly covering extremely backward angles. Differential cross sections, photon beam asymmetries, and spin density matrix elements were measured for the reactions $\gamma p \to \pi^0 p$, $\eta p$, and $\omega p$. Characteristic behaviors have been found in the photon beam asymmetry of $\pi^0$ photoproduction and the differential cross section of $\eta$ photoproduction. An analysis for $\eta'$ photoproduction is also on-going to explore high-mass nucleon resonances.

Currently, BGOegg phase-2 experiment is running with a new setup, where the planar DC and the RPC wall have been removed. Instead, an additional calorimeter system made by $PbWO_4$ (PWO) crystals is installed into the forward acceptance hole. In addition, the photon beam intensity is improved by introducing new pulsed lasers. The phase-2 experiment mainly aims the study for in-medium hadron mass by using a nuclear target, but the data collection with a liquid hydrogen or deuterium target is also planned in near future. Then, it becomes possible to study the isospin structure of baryon resonances by exciting neutrons and also to analyze multi-meson photoproduction which must be sensitive to high-mass resonances. In photoproduction of two mesons, it can be expected that the polarization observables defined in three-body kinematics and for a linearly polarized photon beam [12] will be measured.

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