RECENT PROGRESS AND PROSPECTS OF THE LEPS2/BGOegg EXPERIMENT AT SPring-8*

NORIHITO MURAMATSU

for the LEPS2/BGOegg Collaboration

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

(Received September 30, 2019)

The BGOegg experiment has extensively studied baryon resonances via single meson photoproduction off the proton. In parallel, η' mass inside the carbon nucleus has been intensively investigated in two complementary analyses. Recent results are described with the near future plans.

DOI:10.5506/APhysPolB.51.231

1. Introduction

At SPring-8 LEPS2 beamline, a tagged photon beam is available in the energy range of 1.3–2.4 GeV by laser Compton scattering [1]. A beam intensity reaches $1–5 \times 10^6$ cps. The BGOegg experiment has been carried out in the first phase of LEPS2 beamline operation. In 2014–2016, experimental data have been alternatively collected by using a 54 mm-thick liquid hydrogen target or a 20 mm-thick carbon target. The polar angles from 24° to 144° around the target are covered by an electromagnetic calorimeter, which consists of $1,320$ BGO crystals in an egg shape and is, therefore, called "BGOegg". The charge identification of BGOegg calorimeter hits is done by using inner plastic scintillators (IPS), arranged in a cylindrical shape. The energy resolution of the BGOegg calorimeter is 1.3% for 1 GeV γ rays, providing the world-highest performance [2]. For the forward acceptance hole of the BGOegg calorimeter, a planar drift chamber (DC) and resistive plate chambers (RPC) are placed to detect charged particles.

* Presented at the 3rd Jagiellonian Symposium on Fundamental and Applied Subatomic Physics, Kraków, Poland, June 23–28, 2019.

2. Single meson photoproduction off the proton

We have analyzed the liquid hydrogen target data in order to search for baryon resonances in the s-channel of single meson photoproduction reactions, such as $\gamma p \to \pi^0 p$, ηp, and ωp. The masses and widths of baryon resonances are not well-described by constituent quark models, except for ground and low excited states. Experimental investigation of baryon mass spectra is recognized to be important for understanding hadron structures. Since the excited baryon states have wide widths and overlap with each other, it is effective to measure photon beam asymmetries using an advantage of linear polarization at the LEPS2 beamline and to extract weaker amplitudes from highly excited states through interference. The existing results of photon beam asymmetries are insufficient in the photon beam energy range of 2 GeV or more for all the above reaction modes. The BGOegg experiment has obtained such new experimental results.

In the analyses, the π^0 and η mesons are identified by detecting a $\gamma\gamma$ decay, and the ω meson is reconstructed from a $\pi^0\gamma$ decay. The energy and flying direction of those final-state γs are measured at the BGOegg calorimeter. A recoil proton is detected by the BGOegg calorimeter or the forward drift chamber to measure its emission angle. Then, a kinematic fit is performed by requiring four-momentum conservation. Here, the invariant mass of $\gamma\gamma$ is also constrained to the nominal value of π^0 or η available from the Particle Data Group [3]. A χ^2 probability cut after the kinematic fit eliminates backgrounds, resulting in the clean signal samples of π^0, η, and ω photoproduction of about 650 K, 56 K, and 37 K events, respectively.

The detailed results of differential cross sections and photon beam asymmetries for π^0 photoproduction are described in another paper [4]. The obtained differential cross sections generally agree with the results of CLAS, GRAAL, and LEPS experiments [5–7]. On the other hand, a difference from the CB-ELSA and CBELSA/TAPS results is seen for backward π^0 production angles in the low-energy region of $E_\gamma < 1.9$ GeV [8, 9]. As for the photon beam asymmetries, we have achieved a wide angle coverage at $E_\gamma > 1.9$ GeV, for the first time. A steep drop of the photon beam asymmetry has been observed at extremely backward π^0 angles in this high-energy region, as shown in Fig. 1. None of the existing partial wave analysis models reproduce the measured photon beam asymmetries at high energies [10, 11]. In the analyses for η and ω photoproduction, the measurements of differential cross sections and photon beam asymmetries are also in progress, showing differences from the existing partial wave analysis models in the high-energy region where the multipole amplitudes are not well-fixed. In particular, the differential cross sections of η photoproduction at the most backward angles suggests a wide bump structure around $\sqrt{s} \sim 2.2$ GeV.

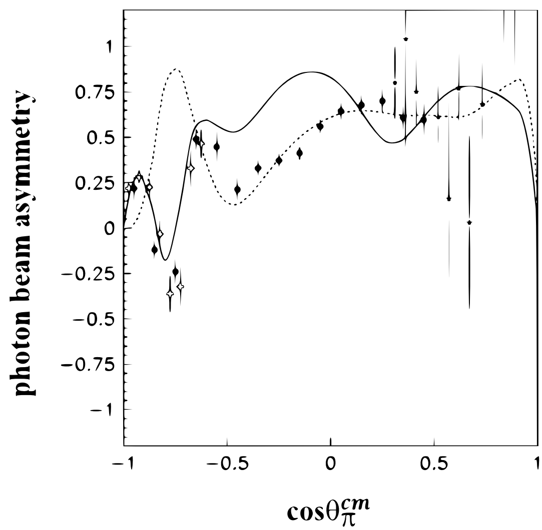

Fig. 1. Photon beam asymmetries measured by BGOegg (closed circles), LEPS (open crosses), and Daresbury (closed stars) at $2200 < E_\gamma < 2300$ MeV. Solid and dashed curves represent partial wave analysis calculations by SAID and Bonn–Gatchina groups, respectively.

3. η'-meson mass in nuclei

The η' meson gains a large mass due to the $\mathrm{U}_A(1)$ anomaly, and it has been discussed that its mass may be reduced inside a nucleus by the partial restoration of chiral symmetry breaking under a high-density environment. While theoretical calculations using the linear sigma model [12] and the NJL model [13] have derived a large mass reduction of 80–150 MeV/c^2, the Quark Meson Coupling model [14] predicts a moderate mass shift of about -40 MeV/c^2. From the experimental side, smaller amounts of mass reduction, which do not exceed 50 MeV/c^2, have been indirectly suggested by the $\eta' N$ scattering length measurement at COSY-11 [15], and the measurements of transparency ratio and sub-threshold cross sections at CBELSA/TAPS [16, 17]. In the BGOegg experiment, we are aiming for more direct observation of an η' mass change by using the carbon target data. For this purpose, we have adopted two analysis methods, as described in the following subsections.

3.1. Medium modification of the η' mass

In order to explore the change of η'-meson mass in carbon nuclei, we detect $\eta' \to \gamma\gamma$ decays, whose branching fraction in vacuum is 2.22%, at the BGOegg calorimeter, and measure the invariant mass distribution of two γ rays. There is a benefit that the calorimeter can detect those

γ rays without much influence of interaction in the target substance. As the produced η' meson has a smaller momentum, the rate of decay in the carbon nucleus increases, possibly enhancing mass reduction signals below the peak structure due to η' decays outside the nucleus in the $\gamma\gamma$-invariant mass distribution.

In searching for the medium modification of the η' mass, it is essential to understand the $\gamma\gamma$-invariant mass spectrum of decays outside the nucleus. This shape is evaluated by a realistic Monte Carlo (MC) simulation that reproduces the detector setup and response of the BGOegg experiment. The validity of the mass resolutions in MC simulations is confirmed in any momentum range by the real data resolutions for the processes $\eta \to \gamma\gamma$ and $\omega \to \pi^0\gamma \to \gamma\gamma\gamma$. In addition, photoproduction of multiple π^0s, $\pi^0\eta$, *etc.* are large background sources that produce many γ rays in the final state but look like signals by missing some of γs in the forward acceptance hole of the BGOegg calorimeter. The reaction $\gamma p' \to \pi^0\pi^0 p$ dominates such backgrounds, while there remain unphysical processes originating from calorimeter hits by cosmic rays and upstream interactions in the region of a large invariant mass. It has been confirmed that the mass spectrum added by the ratio of these processes can be reasonably fitted with a smooth function represented by $\exp(p_0 + p_1 x + p_2 x^2)$. The χ^2 for this overall fit does not change even if variation is given to the background ratio.

The obtained background spectra have been simultaneously fitted to the $\gamma\gamma$-invariant mass distribution in the real data, as shown in Fig 2. This figure is plotted for events where the momenta of η' mesons are over 1 GeV/c.

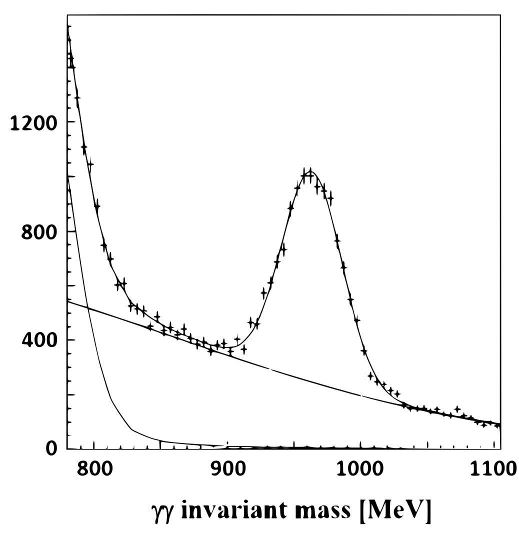

Fig. 2. A background fit to the $\gamma\gamma$-invariant mass distribution in the carbon target data. η' momenta are required to be greater than 1 GeV/c.

In the small invariant mass region, a background component due to the reaction $\omega \to \pi^0\gamma \to \gamma\gamma\gamma$ with a missing γ ray is also considered. The reduced χ^2 of the background fit for the high momentum region is 61.8/59, indicating no signals of medium modification. For more quantitative evaluation of statistical significance, the invariant mass distributions of medium modification signals are derived from simulations with various assumptions of mass reduction and width. Then, χ^2 fits are performed in two cases, when only the background functions are fitted and when the signal function is additionally included. The signal significance is calculated based on the difference of χ^2s. The final significance evaluation will be carried out for the low-momentum region.

3.2. η'-bound nuclei

As another way to probe the η'-mass reduction inside the nucleus, we are also searching for bound states of the η' meson in carbon nuclei. In this method, high-energy protons emitted to extremely forward angles are detected by RPC for tagging photoproduction of low-momentum η' mesons. Proton momenta are measured from time-of-flight with high precision, and missing masses for the $C(\gamma, p)$ reaction are calculated to seek the bound state signals below the threshold of quasi-free η' production. Furthermore, we increase an S/N ratio by using the BGOegg calorimeter, which detects signals that the bound η' mesons are absorbed by protons in the nucleus and cause conversions to back-to-back η–p. Because the nuclear absorption rate of the η' meson is unknown, it is ideal to advance the two complementary analyses with the $\gamma\gamma$-invariant mass and the $C(\gamma, p)$ missing mass.

The search for the nuclear bound states of the η' meson has been performed earlier in the $C(p, d)$ reaction experiment at GSI, resulting in no sign of such signals in the missing mass distribution [18]. In contrast, the BGOegg experiment is characterized by detecting the absorption and conversion signals at the same time. The BGOegg experiment can also detect quasi-free photoproduction of η' mesons, enabling the normalization of theoretical predictions for the differential cross sections of bound signals. Importance of this point is understandable from the pionic atom experiments, where the bound level spectrum has been well-reproduced by theoretical calculations but it has been difficult to match their magnitudes of differential cross sections. We have measured the experimental yield of η' escapes from the carbon nucleus in the decay mode into $\gamma\gamma$, indicating it to be about 1/4 of the theoretical calculation [19].

In the analysis detecting the conversion signals to η–p, the processes like η photoproduction with a scattering of the reaction product from other nucleons remain as final backgrounds. These backgrounds have kinematic features such as η mesons or protons are produced in the forward direction.

Event selection conditions with a sufficient S/N ratio for signal detection are being determined, and the existence of bound signals will be inspected in the $C(\gamma, p)$ missing mass distribution for comparison with the theoretical calculation based on the NJL model [19].

3.3. Near future plan

The forward detectors for charged particles, used in the first-phase BGOegg experiment, have been replaced by an additional electromagnetic calorimeter, called a "Forward Gamma" detector. It consists of 252 PWO crystals, each of which has a size of $22 \times 22 \times 180$ mm^3. The charge of a calorimeter hit is identified by a two-dimensional hodoscope array (Forward Plastic Scintillators). By covering most of solid angles with calorimeters, an ambiguity of judging reaction processes due to missing particles are efficiently reduced. In terms of the medium modification search for the η' meson, a main background coming from the reaction $\gamma p' \to \pi^0\pi^0 p$ decreases less than one order of magnitudes. This feature provides great advantage in suppressing fluctuation of a background spectrum, which fakes medium modification signals.

In the BGOegg experiment, the target is being changed to copper, which has a larger nuclear radius, for further data collection using the new detector setup described above. In 2017, we have collected test data with a copper target, whose thickness corresponds to 0.1 radiation length in the same way as the previous program with a carbon target. Because the uncertainty of a reaction point is reduced by decreasing target thickness from 20 mm to 1.5 mm, the resolution of $\gamma\gamma$-invariant mass for η' is improved from 20 MeV/c^2 to 13 MeV/c^2. In 2018, we have increased the copper target thickness by a factor of 5, and finished short-term data taking with partial operation of the new detectors. The BGOegg experiment will be resumed after the preparation of a data acquisition system is completed. Figure 3 shows the sensitivity of medium modification signals that can be achieved by planned data collection as a function of the binding energy. It is assumed that a copper target with 0.5 radiation length will be irradiated by a photon beam of 2×10^6 cps for 4 months with the new experimental setup. The vertical axis represents 90% upper limits for a background fluctuation of $\sigma \sim 13$ MeV/c^2 to be recognized as signals in the form of a percentage to the quasi-free η' photoproduction. If the momentum range of produced η' mesons is limited up to several hundreds MeV/c, the rate of $\gamma\gamma$ decays inside the nucleus is expected to be a few percent, so this data collection must provide enough sensitivity.

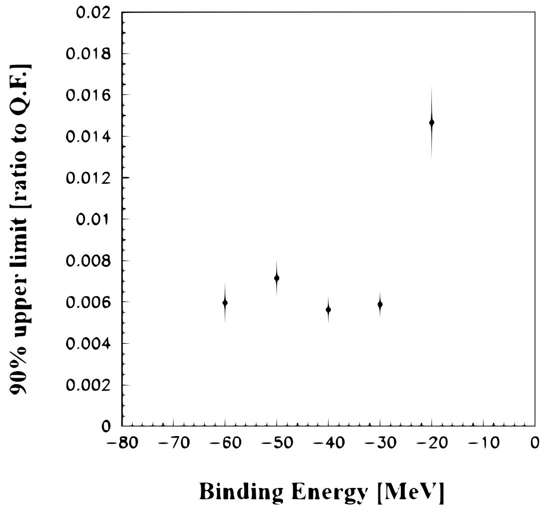

Fig. 3. Sensitivity of η' mass modification for the near future BGOegg experiment using a copper target.

4. Summary

The BGOegg experiment is conducted for research programs to understand hadron natures by using a 1.3–2.4 GeV photon beam at the SPring-8 LEPS2 beamline. Data collected using a liquid hydrogen target is analyzed to search for baryon resonances. In particular, photon beam asymmetries have been measured with the advantage of high linear polarization in a high-energy region where experimental results are scarce. The same data will be further utilized to study highly excited baryons through the photoproduction of η' or multiple mesons. In addition, we analyze the carbon target data to investigate medium modification of the η' mass in the $\gamma\gamma$-invariant mass and to search for nuclear bound states in the $C(\gamma, p)$ missing mass. In the near future, we will use a thicker copper target and employ mostly full coverage by two types of electromagnetic calorimeters. Medium modification signals can be detected with sufficient statistical accuracy in half-year data collection. The new experimental setup allows the detection of all final-state particles with charge identification, and enables data collection even for a deuterium target.

REFERENCES

[1] N. Muramatsu *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **737**, 184 (2014).
[2] T. Ishikawa *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **837**, 109 (2016).
[3] M. Tanabashi *et al.* [Particle Data Group], *Phys. Rev. D* **98**, 030001 (2018).
[4] N. Muramatsu *et al.*, *Phys. Rev. C* **100**, 055202 (2019).
[5] M. Dugger *et al.*, *Phys. Rev. C* **76**, 025211 (2007).
[6] O. Bartalini *et al.*, *Eur. Phys. J. A* **26**, 399 (2005).
[7] M. Sumihama *et al.*, *Phys. Lett. B* **657**, 32 (2007).
[8] O. Bartholomy *et al.*, *Phys. Rev. Lett.* **94**, 012003 (2005).
[9] V. Crede *et al.*, *Phys. Rev. C* **84**, 055203 (2011).
[10] `http://gwdac.phys.gwu.edu/`
[11] `https://pwa.hiskp.uni-bonn.de/`
[12] S. Sakai, D. Jido, *Phys. Rev. C* **88**, 064906 (2013).
[13] H. Nagahiro, M. Takizawa, S. Hirenzaki, *Phys. Rev. C* **74**, 045203 (2006).
[14] S.D. Bass, A.W. Thomas, *Phys. Lett. B* **634**, 368 (2006).
[15] E. Czerwiński *et al.*, *Phys. Rev. Lett.* **113**, 062004 (2014).
[16] M. Nanova *et al.*, *Phys. Lett. B* **710**, 600 (2012).
[17] M. Nanova *et al.*, *Phys. Lett. B* **727**, 417 (2013).
[18] Y.K. Tanaka *et al.*, *Phys. Rev. Lett.* **117**, 202501 (2016).
[19] H. Nagahiro, *JPS Conf. Proc.* **13**, 010010 (2017).