The status and prospect of the SPring-8/LEPS2 BGOegg experiments

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1 Introduction

The BGOegg collaboration has been formed in 2012 for the purpose to investigate the origin of mass and the hadron properties through the photoproduction of mesons decaying into photons. The experiments are carried out at the SPring-8/LEPS2 beamline (BL31LEP) under the cooperation by ELPH (Tohoku University), RCNP (Osaka University), Kyoto University, KEK, RIKEN, JASRI (SPring-8), and several institutes in the world. After moving the BGOegg calorimeter from ELPH to the LEPS2 experimental building in 2012 December, the installation of photomultipliers with high voltage supply and signal readout for 1,320 BGO ($Bi_4Ge_3O_{12}$) crystals were done in 2013. The other detectors and the DAQ system were also prepared in parallel. We have started the physics data collection from 2014 April.

As one of the main physics goals, we search for the η'-mesic nuclei. The mass of the η' meson is distinctively larger than those of the other psuedoscalar mesons because of the $\mathrm{U}_A(1)$ anomaly, and the theories based on the Nambu-Jona-Lasinio (NJL) model [1] and the linear sigma model [2] expect the η' mass reduction by 80–150 MeV at the nuclear density as a result of the partial restoration of the chiral symmetry breaking. The lighter η' meson bound in a nucleus is usually searched for in the missing mass spectrum of $A(\gamma, p)$ with the detection of a forward proton, but the signal-to-noise ratio is too small for the experimental identification. Therefore, the BGOegg experiment plans to improve that ratio by detecting the nuclear absorption signals of the bound η' at the BGOegg calorimeter.

We also aim to reveal the hadron pictures through the resonances of meson(s)-baryon and meson-meson systems. For example, the excited nucleon resonances are under studies in the s-channel of single or double meson (η, η', ω, $\pi^0\pi^0$, $\pi^0\eta$, etc) photoproduction. The coupling strengths to individual final states depend on the possible configuration of isospin, quark flavor, and so on. At the LEPS2 beamline, the highly lenear polarized photon beam is available, so that the measurement of the photon beam asymmetry in addition to the differential cross section must provide the helicity amplitudes of the reaction or the spin information of the resonances.

2 Experimental setup and status

The intensity of the tagged photon beam was 1.4–1.8 MHz with the simultaneous injection of three or four ultraviolet lasers (8/16/24 W "Paladin" by Coherent Inc.) into the 8 GeV electron storage ring [3]. The further improvement of the intensity is under considerations with the updates of optics and lasers. The laser wavelength of 355 nm gives the maximum photon beam energy of 2.4 GeV by the backward Compton scattering, while the geometrical acceptance of the LEPS2 tagging detector for recoil electrons enables to lower the tagging energy range down to 1.3 GeV. The laser polarization control system with wave plates has been introduced for changing

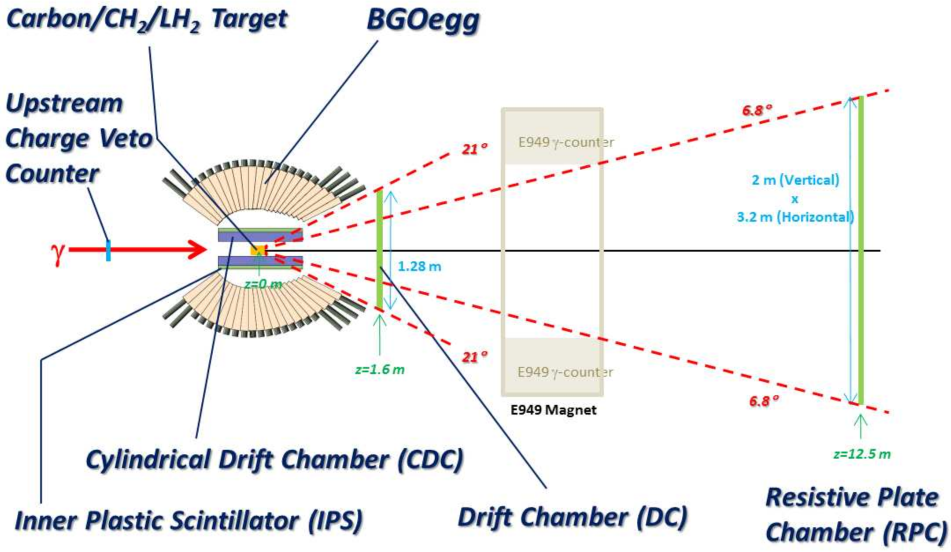

Figure 1: Setup of the BGOegg experiments. The forward acceptance hole of the BGOegg calorimeter ($\theta < 24°$) is mostly covered by the drift chamber ($\theta < 21°$). The size of the RPC wall was determined by the bore diameter of E949 solenoid magnet.

the linear polarizations in the vertical or horizontal directions and checking the geometrical asymmetry effect in the spin observables.

The produced photon beam is delivered to the 135 m-downstream experimental building with the final beam spread of about 6.5 mm in σ [4]. In the first half of 2014 (2014A), a 20 mm-thick polyethylene (CH_2) or carbon (ρ=1.73 g/cm^3) block was alternatively placed as a fixed target for the initial calibration purpose and the η'-mesic nuclei search. In parallel, the liquid target system for hydrogen or deuterium was developed with a 40 mm-thick cell made of polyimide films. The liquid hydrogen (LH_2) target was exposed in the latter half of 2014 (2014B).

Figure 1 shows the setup of BGOegg experiments. The BGOegg electromagnetic calorimeter surrounds the target with the shape of an "egg", covering the polar angles from 24° to 144°. Individual BGO crystals occupy one of the 60 azimuthal sectors and 22 polar layers with the depth of 20 radiation lengths. The energy resolution is 1.3% at 1 GeV [5], providing one of the world highest performance. The channel-by-channel adjustment of the photomultiplier gains became available with the high voltage distributor from 2014 May, so that the output signals were calibrated to be about 1 mV per 1 MeV. The standard trigger was made by the logic signal with two or more BGO crystal hits in coincidence with the tagging detector signal. The trigger rate was typically $\sim$500 and $\sim$200 Hz with the carbon and LH_2 targets, respectively.

Charged particle hits at the BGOegg calorimeter are identified by the inner plastic scintillators (IPS) and the cylindrical drift chamber (CDC). The IPSs are azimuthally divided into 30 sectors with the single-end readout by the multi-pixel photon counters. The energy loss information at the IPS is also used for the separation of proton and pion bands in the correlation plot with the kinetic energy measured at the BGOegg calorimeter, as shown in Fig. 2.

The forward acceptance hole of the BGOegg calorimeter is covered by the planar drift chamber (DC) and the resistive plate chambers (RPC) [6], which have been originally developed for the use at the LEPS2 solenoid experiments. This setup is convenient for the mesic nuclei search, which needs to detect a forward proton. The DC with six wire planes in three directions works well to reduce the backgrounds where the DC track angle is kinematically inconsistent with the prediction by the missing momentum at the BGOegg calorimeter. A wall of the RPCs is located at the 12.5 m downstream of the target in order to measure the time-of-flight (TOF) of a proton, flying into the polar angle region less than 7°. The RPCs were installed in 2014 May, and stably operated from the middle of June.

3 Collected data

In 2014, the integrated number of tagged photons reach 10^{13} in total for the physics runs. The statistics of the individual data sets with different targets and polarizations are summarized in Table 3, along with the information for the first half of 2015 data taking (2015A). Because of the materials from the Compton scattering

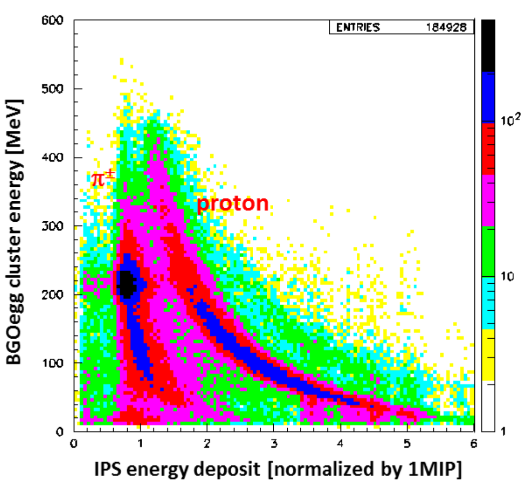

Figure 2: The scatter plot of the kinetic energy measured at the BGOegg calorimeter versus the energy deposit at IPS. Events with the hit at the BGOegg calorimeter layer 7 are plotted.

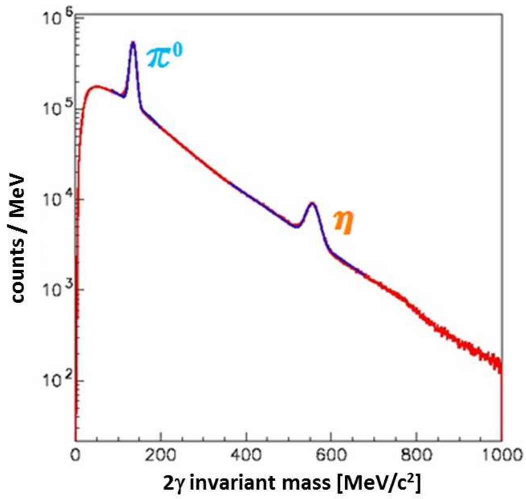

Figure 3: The invariant mass spectrum of two photons detected at the BGOegg calorimeter with the 20 mm-thick nuclear targets used in 2014A.

point to the LEPS2 experimental hall, the number of photons at the target is reduced to about 80% of the tagged counts. In 2014A, we accumulated 4.3×10^{12} tagged photon counts for the carbon target, but the RPC, which is necessary for the analyisis of η'-mesic nuclei search, was available only for $\sim$30% of the sample. For this data with RPC, the yield of η'-mesic nuclei signals at the proton polar angles less than 6° are expected to be a few hundred events by assuming the cross section based on the NJL model [1]. The number of detected signals will be reduced much when the nuclear absorption signals are tagged. Therefore, we used the 2014A data as the test sample of this analysis, and collected 7 times higher statistics data in 2015A. In 2014B, we took roughly equivalent amouts of two data sets with the vertical and horizontal polarizations of the photon beam. These are new data with the highest polarization beam by laser Compton scattering in the energy region around 2 GeV. In order to compete with the CB-ELSA and CLAS data using a bremsstrahlung beam, we are further accumulating the LH_2 target data in the latter half of 2015 (2015B).

The calibrations of the collected data and the development of the event reconstruction programs are now in progress. Figure 3 shows the invariant mass spectrum for the two photons, reconstructed as the clusters of fired BGO crystals without the corresponding IPS hit. The energy calibration of 1,320 crystals has been iterated to adjust the $\pi^0 \to 2\gamma$ mass peak at the nominal value [7] by scaling the energy of the final state photon together with the energy leak correction at each crystal. The mass resolutions of π^0 and η are 6.7 and 14.4 MeV/c^2, respectively, which are consistent with the MC simulation results. These values are the best among the world calorimeter experiments including TAPS, CB-ELSA, and BGO-OD since the energy resolution and detector granularity of the BGOegg calorimeter are better.

The TOF at RPC is measured by using the reference time based on the accelerator radio-frequency (RF) signal, which comes in each 2 ns. The true electron bunch where the Compton scattering happened was solved by taking a coincidence with the tagging detector signal. The RPC time resolutions, measured from the $e^\pm$ TOF

Table 1: Statistics of the data collected at the BGOegg experiments. The integrated number of tagged photons is evaluated by correcting the tagging detector counts by the trigger dead time. The numbers in parentheses at 2014A indicate the statistics for the case the RPC was stably operated. In 2015A, most of the data was collected with a vertical polarization beam.

Period	Target	Integrated number of tagged photons
2014A (Apr.–July)	Carbon/CH_2 (20 mm-thick)	C: 4.29×10^{12} (1.31×10^{12}) CH_2: 2.56×10^{12} (1.58×10^{12})
2014B (Nov.–Feb.)	LH_2 (40 mm-thick)	Hori: 2.24×10^{12} Vert: 2.01×10^{12}
2015A (Apr.–July)	Carbon (20 mm-thick)	9.77×10^{12} (Vert: 8.97×10^{12})

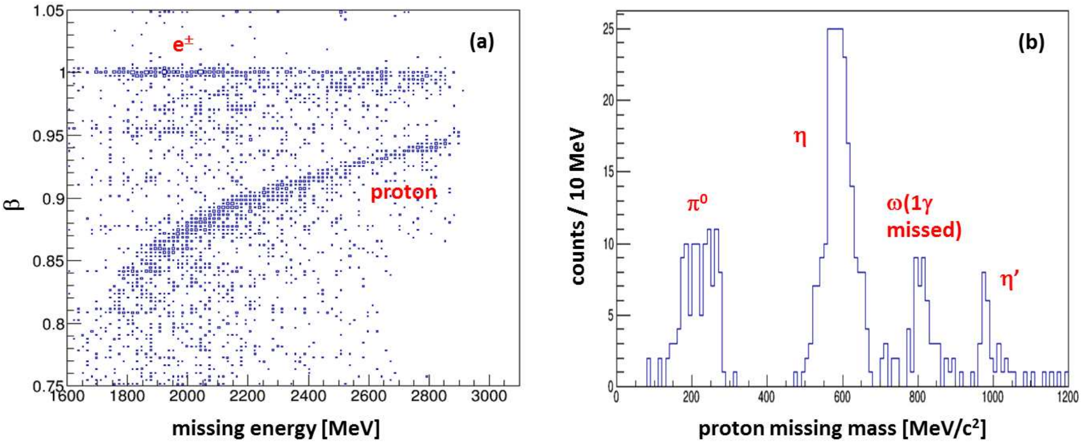

Figure 4: (a) Scatter plot of the β measured at RPC versus the missing energy obtained by the BGOegg calorimeter. (b) Missing mass distribution for the proton whose β was measreud at RPC.

distributions with the correction of flight length depending on the hit position, have been obtained to be 70–80 ps strip by strip. The measured TOF is transformed to β and then a momentum by assuming the proton mass if the β is slow enough. The momentum resolution is about 1% at 2 GeV/c, providing the resolution comparable with the magnetic spectrometer. Figure 4(a) shows the measured β versus the missing energy when π^0 or η is identified at the BGOegg calorimeter. A clear proton band, corresponding to the reaction $\gamma p \to \pi^0 p/\eta p$, is seen. In the case a slow particle is detected at RPC, the missing mass spectrum with the assumption of a proton indicates clear meson peaks, as shown in Fig. 4(b), after requiring the transverse momentum balance with the two photons at the BGOegg calorimeter.

4 Preliminary analyses

As described in the previous section, we analyzed the 2014A carbon data with RPC as the test sample of η'-mesic nuclei search in the reaction $C(\gamma,p)^{11}_{\eta'}B$. First of all, we have developed the event selection conditions for the 1-nucleon absorption signal, where the $\eta' N \to \eta N$ conversion is expected to be dominant [8]. The produced η meson was tagged at the BGOegg calorimeter in the two decay modes of 2γ and $3\pi^0$ with the background reduction more than two order of magnitude instead of the signal acceptance of $\sim$0.1. Figure 5 shows (a) the η tagging in the 2γ invariant mass distribution and (b) the missing mass spectrum of the proton detected at RPC with the carbon mass at the initial state. In Fig. 5(b), the signal region is masked for the η-tagged sample, and the distributions for sideband events and expected signals are overlaid with proper scales. It turns out that the combinatorial background due to the multiple pion production is not significant as seen in the sideband sample and that the η-related backgrounds ($\eta\pi$ production, etc) still remain only with the η tag. However, we can obtain extra reduction factors enough by tagging the opposite proton from the conversion and identifying this proton by IPS. A similar signal-to-noise ratio has been observed also for the $\eta \to 3\pi^0$ tagging mode. We will also take into account the 2-nucleon absorption tagging, where only a back-to-back nucleon pair is detected at the BGOegg calorimeter and IPS.

The analyses using the LH_2 target data are also in progress. The $\pi^0\gamma$ decay mode in the ω photoproduction and the 2γ decay mode in the η and η' photoproduction have been focussed so far to measure the differential cross sections and the photon beam asymmetries. While the photons from those mesons were measured at the BGOegg calorimeter, only one additional track with charge was allowed at either of the DC or BGOegg calorimeter. The angle consistency between the charged track and the missing momentum of the detected meson was also required for background reduction. In the 2014B data, about 33K, 44K, and 1,200 events are counted for the ω, η, and η' events, respectively. These statistics will be increased by the tagger and IPS analysis upgrades, the use of different decay modes, and the addition of the 2015B data. Figure 6 shows the azimuthal asymmetry pattern of the ω photoproduction yield without binning the energy and polar angle ranges and taking into account the beam polarization degree. In both the vertical and horizontal polarization data, the asymmetry patterns are well seen with $\sim 90°$ phase difference. Clear asymmetry patterns have been also observed in the η and η' photoproduction.

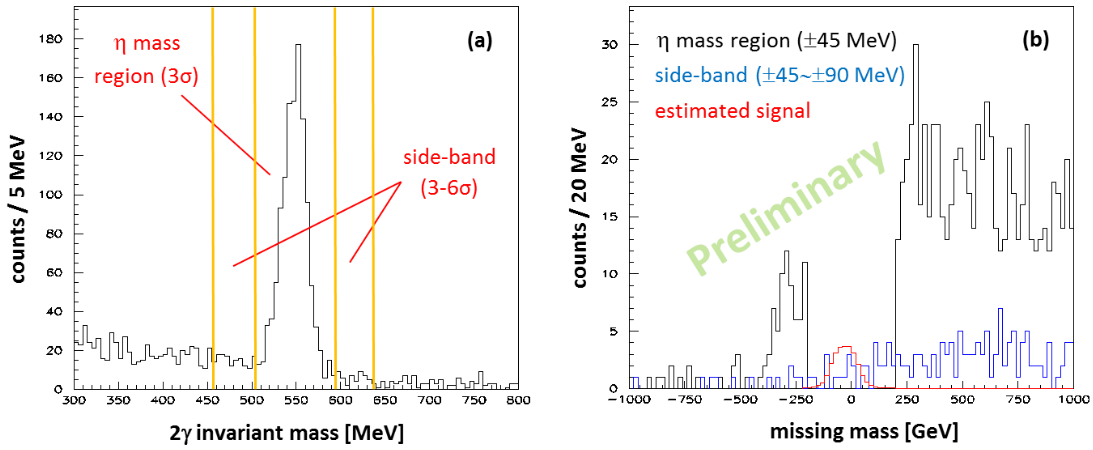

Figure 5: (a) 2γ invariant mass distribution around the η mass with the forward proton detection at RPC. Additional tracks are not allowed except for a proton candidate opposite to the η. (b) Missing mass distributions for the reaction $C(\gamma, p)X$ with the subtraction of the ^{11}B and nominal η' masses. Two cases with the η tagging and its sideband selection are simultaneously plotted together with the signal expectation. The signal region is masked for the η-tagged sample.

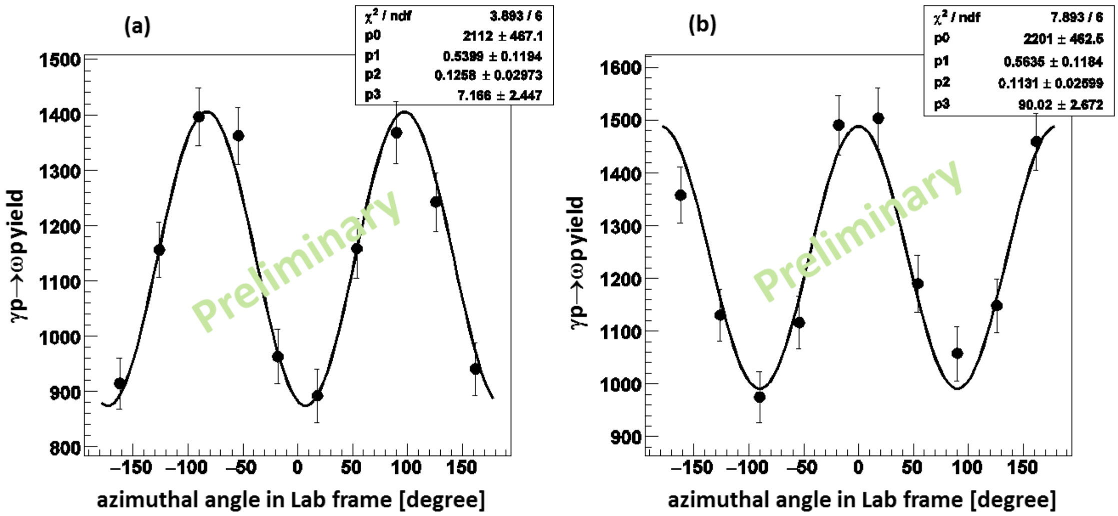

Figure 6: Azimuthal asymmetry patterns of the ω photoproduction yield for (a) vertically and (b) horizontally polarized photon beams.

5 Summary and prospect

The LEPS2/BGOegg collaboration has started the physics data collection from 2014 April by using the carbon, polyethylene, or liquid hydrogen target with the 1.3–2.4 GeV photon beam. So far there has been progress in preparing the event reconstruction programs and understanding the detector responses with precise calibrations. We have achieved good resolutions for the energy measurement at the BGOegg calorimeter and the TOF measurement at RPC. Their performance satisfies our physics motivation about the η'-mesic nuclei search, the nucleon resonance studies through meson photoproduction, etc.

On the η'-mesic nuclei search, we have started the background reduction studies by tagging the 1-nucleon absorption signal of the bound η'. Further improvements of the signal-to-noise ratio will be achieved in both 1-nucleon and 2-nucleon absorption modes. We have already added 7 times higher statistics data with the carbon target in 2015A. We will be able to examine the existence of the η'-mesic niclei at the level predicted by the models with deep binding energies.

For the LH_2 target data, we are first going to obtain the photon beam asymmetries in the ω, η, and η' photoproduction. The differential cross sections will be then measured with the systematic understanding of acceptance and normalization. Additional LH_2 data with an equivalent amount will be available in 2015B for further accumulation of the statistics, which enables the analyses for multiple meson photoproduction, K^0_S-associated modes, etc. In addition, we will take the liquid deuterium target data in 2016 for the studies of γn reactions.

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