First Beam Observation and Near Future Plans at SPring-8 LEPS2 Experiments

N. Muramatsu for the LEPS2 Collaboration
Research Center for Electron Photon Science, Tohoku University
1-2-1 Mikamine, Taihaku, Sendai, Miyagi 982-0826, Japan

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Abstract
The first photon beam was successfully produced by laser Compton backscattering at the LEPS2 beamline, which was newly constructed at SPring-8 for the purpose to increase the beam intensity one order of magnitude more than that of the LEPS experiments and to achieve the large acceptance coverage with high resolution detectors. The BGOegg electromagnetic calorimeter with associated detectors are being set up at the LEPS2 experimental building for the physics programs, including the searches for \( \eta' \)-bound nuclei and highly excited baryon resonances. In parallel to the BGOegg experiments, the LEPS2 charged particle spectrometer will be prepared inside the 1 Tesla solenoidal magnet, transported from the BNL-E949 experiment.

1 From LEPS to LEPS2

At the LEPS experiments, which started from 1999, the ultraviolet (UV) laser light with the wavelength of 355 nm has been injected into the 8 GeV electron storage ring in order to produce the laser Compton backscattering (LCS) photon beam [1]. The beam intensity has exceeded \( \sim 10^6 \text{ Hz} \) in the tagged photon energy range of 1.5–2.4 GeV. High polarization is transferred from the laser light to the photon beam, so that the t-channel exchange reaction with a forward meson photoproduction is usable as a parity filter. Such reactions have been extensively investigated by the LEPS forward spectrometer, which covers the polar angle region within \( \pm 20^\circ \) and \( \pm 10^\circ \) in the horizontal and vertical directions, respectively. For example, we have analyzed the forward \( K^{*0} \rightarrow K^\mp \pi^- \) production from a proton target with the identification of the associated \( \Sigma^+ \) in the missing mass distribution [2]. In this study, the LCS photon beam energy was upgraded up to 2.9 GeV by using a deep UV laser. The dominance of natural parity exchange in the t-channel was observed based on the parity spin asymmetry measurement, indicating the evidence of the controversial scalar meson \( \kappa(800) \).

On the other hand, the further systematic studies of hadron photoproduction generally require larger acceptance coverage and higher photon beam intensity. Recently, we measured the differential cross sections of backward \( \eta' \) photoproduction with the forward proton detection at the LEPS forward spectrometer [3]. It was suggested that the bump structure at \( W \sim 2.3 \text{ GeV} \) may be enhanced in the most backward angles, which are not covered by the CLAS experiments [4]. There may be a resonance contribution with a high angular momentum, but it is needed to increase the statistics possibly with a wide angular acceptance. Because of the demands represented by this measurement, we are motivated to start the LEPS2 project at another beamline of SPring-8 [5].
Figure 1: (a) Photon beam spread at the 135 m downstream from the Compton scattering point. The solid line comes from the purely kinematical calculation of backward Compton scattering. Actually, it is smeared by the electron beam divergences at the LEPS and LEPS2 beamlines, as shown in the shaded areas (corresponding to RMS). (b) The schematic view of the LEPS2 facility around the newly installed vacuum chambers and the laser side-injection system.

2 LEPS2 Facility

The LEPS2 beamline utilizes a 30 m-long straight section, the number of which is limited to only 4 of the 62 beamlines at SPring-8. The horizontal divergence of the electron beam at this straight section is reduced to 14 μrad in σ, while the usual 7.8 m-long straight section including the LEPS beamline provides the divergence of 58 μrad. As shown in Fig. 1(a), the LCS photon beam spread at the LEPS2 beamline is determined not largely by the electron beam divergence but mostly by the Compton scattering angle, which is calculated by the kinematics depending on the photon energy. This achieves a well collimated photon beam with the radius below 10 mm even at the 135 m downstream from the Compton scattering point, enabling us to construct a large experimental site outside the storage ring building.

We also aim to increase the tagged photon beam intensity nearly up to $10^7$ Hz for the photon energy range below 2.4 GeV by using the UV lasers with the wavelength of 355 nm. We plan the simultaneous injection of four lasers, whose output power have increased from 8 W to 16 W or 24 W. The multiple laser operation has become possible thanks to the reduced electric power consumption of those new lasers. For the simultaneous injection, we have installed new beamline chambers with large apertures [6]. As shown in Fig. 1(b), the laser injection from the side concrete shield wall into the SPring-8 ring tunnel is adopted in order to reduce the total length and apertures of the newly installed chambers. The radiation level at the laser injection room is also lowered with the minimized shield materials, so that we can easily access the laser optics for adjustments. The large mirror to guide the four laser beams from the side direction toward the straight section inside a vacuum chamber has been modified to possess a horizontal slit and a small center hole for avoiding the heat input from x-rays and the $e^+e^-$ conversions of the LCS photon beam, respectively. In addition to the LCS beam with the UV lasers, we plan to improve the intensity of a high energy photon beam using the deep UV lasers with the wavelength of 266 nm. We expect the tagged photon intensity approaching to $10^6$ Hz with the techniques similar to the UV case.

The construction of the LEPS2 beamline was approved in 2010. The LEPS2 experimental site, whose size is 12 m × 18m in area
with the height of 10 m, was built in 2011. The constructed experimental building has the volume 15 times larger than the experimental hutch of the LEPS experiments. In 2011, we also transported the BNL-E949 magnet, which is a 1 Tesla solenoidal magnet with the weight of 400 tons, and successfully installed it into the LEPS2 experimental building. This magnet has the bore diameter of 2.96 m and the inner length of 2.22 m, where the charged particle spectrometer described later will be placed. The beamline vacuum chambers and the laser injection system were finally installed and aligned in late 2012.

### 3 First Beam Observation

After adjusting the electron beam orbit at the straight section and degassing the absorbers and the mask with synchrotron radiation, the first LCS photon beam at the LEPS2 beamline was produced with the injection of a single UV laser beam during the machine study on 27 Jan. 2013. The simultaneous injection of three UV laser beams was then tested on 2 Apr. for the further investigation of beam properties as described below. Figure 2(a) shows the photon energy spectra, which have been measured by a large Bi$_4$Ge$_3$O$_{12}$ (BGO) crystal with the diameter of 8 cm and the length of 30 cm. The blue histogram represents the spectrum for a bremsstrahlung photon beam without laser injection at the electron beam current of 10 mA, while the black histogram shows that for a LCS photon beam with the contamination of a bremsstrahlung beam at the current of 0.1 mA. The two spectra are normalized by the electron beam current, the data taking time, and the DAQ live time. The lowest photon energy part of the LCS beam spectrum is cut off at \( \sim 0.65 \text{ GeV} \) because of a \( \phi 7 \text{ mm} \) lead collimator inside the storage ring tunnel. The intensity of a LCS photon beam, corresponding to the spectrum height, is nearly two orders of magnitude higher than that of a bremsstrahlung beam, although the straight section is long.

The photon beam profile was measured by the 16 ch. \( \times \) 16 ch. two-dimensional array of 3 mm-square scintillating fibers with a 0.5 mm-thick aluminum converter, which was placed between the plastic scintillators for the charge veto and the trigger. We refer to this detector as a beam profile monitor (BPM). As shown in Fig. 2(b), the profile of a bremsstrahlung photon beam is a bit spread with the RMS radius of \( \sim 9 \text{ mm} \) because of the electron beam orbit structure at the 30 m-long straight section. On the other hand, the profile with laser injection is well collimated with the dominance of a LCS photon beam (Fig. 2(c)), resulting in the RMS radius of \( \sim 6 \text{ mm} \) as expected from Fig. 1(a).

The photon beam intensity was measured with the simultaneous three laser injection. The intensity is usually measured by counting the recoil electron rate at the tagger, but its optimization is still underway. Therefore, we
adopted the following two alternative methods for the intensity measurement: One of them is the estimation from the change of electron beam life before and after the laser injection. The electron beam life corresponding to the Compton scattering loss was measured to be \( \sim 120 \) hours. This measurement was performed with the electron beam current of 100 mA, so the backward Compton scattering rate corresponding to the photon beam intensity was calculated to be \( \sim 7 \) MHz for \( 0 < E_\gamma < 2.4 \) GeV. Another estimation was done by the measurement of the \( e^+e^- \) conversion rate at the BPM. The BPM trigger rates were 29.0 kHz and 3.7 kHz for the cases with laser on and off, respectively. By taking into account the pair production cross sections at the converter and the trigger scintillator, the photon beam transmission through the beamline materials (\( \sim 76\% \)), and the cutoff of low energy photons by the collimator, the intensity of a LCS photon beam is calculated to be \( \sim 7 \) MHz, which is consistent with the estimation from the electron beam life. The obtained beam intensity is nearly half of our expectation, so that we are trying to fix the problems of laser injection optics.

4 Experimental Programs

Two different detector setups are being prepared for the experimental programs at the LEPS2 facility. The first experiments will be carried out with the electromagnetic calorimeter called 'BGOegg' from the latter half of FY2013. The calorimeter system has been installed in the upstream part of the LEPS2 experimental building, and covered by a thermostatic booth to avoid the calorimeter gain change which is expected at the level of \(-1.5\%/^\circ\mathrm{C}\). In the center part of the LEPS2 building, the BNL-E949 solenoidal magnet has been set up with a pit hole. We will keep constructing the LEPS2 charged particle spectrometer inside the solenoid during the BGOegg experiments in parallel. The experiments with this spectrometer will follow the BGOegg experiments in a few years.

4.1 BGOegg Experiments

The BGOegg electromagnetic calorimeter is an 'egg'-shaped assembly of 1320 BGO crystals, as shown in Fig. 3(a). Each crystal with the shape of a truncated square pyramid has the longitudinal length of \( \sim 220 \) mm, corresponding to 20 radiation length. The BGO crystals are separately stacked in the forward 13 layers and the backward 9 layers of the 60...
Figure 4: (a) Energy resolutions and (b) position resolutions as a function of the incident energy at the positron beam test of the prototype BGOegg calorimeter. The data points indicated as ‘central’ in (b) were measured by the energy weights in 3×3 BGO crystals with the beam injection into the central crystal. (c) The distribution of 2γ invariant mass measured at the partial operation (only forward 300 channels) of the BGOegg calorimeter. The two histograms, which must be scaled by the indicated magnification factors, are plotted for the different threshold values of an individual γ energy.

crystal ring without partition supports. The BGOegg covers the large geometrical acceptance from 24° to 144° in polar angles. We will install a cylindrical drift chamber (CDC) and plastic scintillators inside the BGOegg for the detection of charged particles. The BGOegg calorimeter was constructed at Research Center for Electron Photon Science (ELPH), Tohoku University, and was successfully transported to SPring-8 in December 2012.

The performance of the BGOegg calorimeter has been examined at ELPH by injecting a positron beam into a 5×5 crystal array with the front coverage by scintillating fiber hodoscopes [7]. As shown in Fig. 4(a), the measured energy resolution varies as a function of the incident energy, resulting in ∆E/E=1.3% at 1 GeV. The positron beam position was also measured from the shower distribution in 3×3 crystals, and was compared with the hodoscope information. The position resolution was estimated to be 3.1 mm at the center part of the crystal array for the incident energy of 1 GeV. (See Fig. 4(b).)

In January 2013, the BGOegg was partially operated at the LEPS2 beamline for a commissioning purpose. Photomultipliers, high voltage suppliers, and a related DAQ system were prepared only for the most forward 5 layers or 300 BGO crystals. A test beam of the LCS photons was irradiated onto a 20 mm-thick carbon target at the BGOegg center. Shower activities which coincide with the tagger signal timing were clustered after the rough gain calibrations of 300 crystals. In Fig. 4(c), two of such clusters were combined to calculate the invariant mass with the different conditions of energy thresholds. A clear peak of the π⁰ → γγ decays is observed with the mass resolution of ∼15 MeV, which is slightly worse than the expected resolution because the precise energy calibrations has not been done. The η → γγ decays require larger opening angles, so the corresponding signal peak is not clear in this plot due to the limited geometrical acceptance.

4.2 Physics Programs expected at the BGOegg Experiments

We are considering to search for the η'-bound nuclei as one of main physics programs at the BGOegg experiments. By the partial restoration of the chiral symmetry, the η' mass is theoretically expected to decrease by ∼150 MeV at a normal nuclear density [8]. This produces a potential for the η' meson to be bound inside a nucleus. Such a state may be accessible by injecting a high energy photon into a nucleus and by striking a proton to the extremely forward direction.
Figure 5: (a) The simulated $\eta'$ recoil momenta as a function of the photon beam energy in the case that the final state proton in the $\gamma p \to \eta' p$ reaction is detected at the RPC, covering the extremely forward angles less than $8.5^\circ$. The photon energy ranges accessible with the UV and deep UV lasers at the LEPS2 experiments are also indicated. (b) The expected momentum resolutions as a function of the proton momentum, measured from the TOF at the RPC. The maximum proton momenta at the various photon energies are also indicated.

At the BGOegg experiments, the forward acceptance hole of the calorimeter is covered by TOF detectors to measure the momenta of charged particles, as shown in Fig. 5(b). For the extremely forward region at $\theta < 8.5^\circ$, a 2 m×4 m wall of resistive plate chambers (RPC), whose individual size is 20 cm×100 cm, will be placed at the 12 m downstream of the target. The time resolution of the RPC was measured by a beam test at the LEPS beamline, and was estimated to be 50 psec [9]. We are planning to cover the forward angles between the RPC wall and the calorimeter ($8.5^\circ < \theta < 24^\circ$) by the TOF wall of plastic scintillators at the just upstream of the E949 solenoid. The positions and angles of forwardly produced charged particles will be measured by a drift chamber (DC), which has an effective diameter of 1280 mm. The DC consists of 6 planes with three different wire angles, possessing 16 mm-square drift cells. The position resolution of 130 $\mu$m has been confirmed at a beam test [10].

The setup of the BGOegg calorimeter with the forward charge detection is suitable for the $\eta'$-bound nuclei search. In the case that the forward proton is detected at the RPC, the recoiled $\eta'$ has a low momentum (∼400 MeV/c) to be bound at a proton hole. (See Fig. 5(a).) The higher photon beam energy with the injection of deep UV laser reduces the lower limit of the recoil momentum further. The momentum resolution for the forward proton detected at the RPC is estimated to be less than 1% as shown in Fig. 5(b). This results in the missing mass resolution of 15 MeV at $E_\gamma = 2.4$ GeV. The BGOegg calorimeter will be used to improve the S/N ratio, and it may be possibly used to detect $\eta'$ decays for a line shape analysis. The $\eta'$ mass resolution by two gamma invariant mass is estimated to be 30 MeV at $E_\gamma = 2.4$ GeV without a kinematical fitting.

The $\eta'$-related physics will be also explored extensively by preparing a liquid hydrogen or deuterium target with a long nose. For example, it may be possible to measure the $\eta'p$ scattering length. This measurement has become possible by extending the lower limit of the tagged photon energy range to 1.35 GeV with the modification of a LEPS2 beamline chamber and by covering the kinematical region well below the $\eta'$ production threshold of $E_\gamma \sim 1.45$ GeV. Our detector setup has the feasibility for this study because, at low photon energies, a proton is directed to the extremely forward angles and the $\eta'$ angle de-
dependence of BGOegg acceptance gets small. At $E_\gamma < 2.4$ GeV, the $\eta'$ yield of the elementary photoproduction process is estimated to be $\sim 60,000$ events $\times$ Branching Fraction $\times$ Acceptance per day by assuming the total cross section of 0.8 $\mu$b, the beam intensity of $10^7$ Hz, and the liquid hydrogen target length of 4 cm.

Highly excited baryon resonances, which are not well explained by the constituent quark model, strongly couple to the final state of multi-mesons and a nucleon. We therefore plan to investigate the double meson photoproduction in the $\pi\pi N$, $\pi\eta N$, and $\eta\eta N$ channels. Especially, the $\eta\eta N$ channel works as an isospin filter, which only allows a resonance with $I=1/2$. Similar studies with partial wave analyses can be done at the CBELSA/TAPS experiments through the various combinations of beam and target polarizations. The BGOegg experiments would be able to contribute to this field with the high linear polarization beam at high energies, while the linear polarization of the CBELSA/TAPS experiments is achievable up to $E_\gamma \sim 1.7$ GeV.

4.3 LEPS2 Charged Particle Spectrometer

After a few years run with the BGOegg detector, the next experiments with the LEPS2 charged particle spectrometer are planned by covering large solid angles, as shown in Fig. 6. The BNL-E949 magnet provides the solenoidal field of 1 Tesla, where we are going to place a time projection chamber (TPC) and DCs as a tracking system. The momentum resolution of about 1% is expected for the polar angle region greater than 10°. Particle identification will be done by a cylindrical side wall of RPCs and a forward wall of TOP counters. A part of the DCs and the RPCs will be recycled from the BGOegg experiments. The most outer part of the barrel region is occupied by the sampling electromagnetic calorimeter, which has been originally used at the E949 experiment, although the energy resolution is expected to be around 10%.

As one of the physics programs with the LEPS2 charged particle spectrometer, we will perform the systematic study of the pentaquark candidate $\Theta^+$, which has not been established yet. The reaction of $\gamma n \rightarrow K^-\Theta^+; \Theta^+ \rightarrow K^0_S p; K^0_S \rightarrow \pi^+\pi^- p$ will be examined because the final state of this mode includes only charged particles. The mass resolution for the $\Theta^+$, which will be reconstructed by the $\pi^+\pi^- p$ invariant mass, is expected to be 6 MeV. On the other hand, we are finalizing the exclusive analysis of the reaction $\gamma n \rightarrow K^-\Theta^+; \Theta^+ \rightarrow K^+ n$ in the LEPS data by taking into account
the importance of the final state nucleon identification \cite{11}. The new data to confirm the observed structure in the K$^+\text{n}$ mass spectrum is being accumulated with the LEPS forward spectrometer, whose trigger counter has been enlarged for more efficient detection of a proton.

5 Summary

We have constructed a new laser Compton backscattering beamline (LEPS2) at SPring-8, aiming one order of magnitude higher intensity and larger acceptance coverage compared with the LEPS experiments. We have successfully obtained the first photon beam at the LEPS2 beamline, resulting in the beam size of $\sigma \sim 6$ mm and the intensity of $\sim 7$ MHz for $0 < E_\gamma < 2.4$ GeV. The photon energy spectrum has been also measured using a large BGO crystal.

We will start the BGOegg calorimeter experiments from the latter half of FY2013 with the forward coverage by TOF detectors and a DC. We will carry out $\eta'$-related physics programs, double meson photoproduction studies, etc. The momentum resolution less than 1% is expected for the proton which is detected by the RPC, and the $\eta'$ mass resolution in the $2\gamma$ decay mode is estimated to be $\sim 3\%$ without a kinematical fitting. Experiments with the LEPS2 charged particle spectrometer will follow the BGOegg experiments in a few years. Physics results at the LEPS experiments will be upgraded.

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