Recent Progress and Prospects of the LEPS2/BGOegg experiment at SPring-8

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  Photoproduction experiments by a Laser Compton Scattering (LCS) beam.

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  Measurement of **differential cross section** & **photon beam asymmetry**

➢ Studies of *η’ mass in nuclei*
  Two independent searches for **medium modification** & **mesic nuclei**

➢ **Near future Plan** of BGOegg experiment
  Detector upgrade & sensitivity for the *η’ medium modification search*

➢ **Summary**
SPring-8 LEPS2 Project

SPring-8 (Storage ring of 8 GeV e⁻ w/ 100 mA)

LEPS2 Experimental Building (2013 ~ )

LEPS Experimental Hutch (1999 ~ )

SPring-8

Booster Synchrotron

XFEL SACL

New SUBARU

457 m

Ehara 1 GeV
Simultaneous injection of Max. 4-Lasers

- 355 nm UV laser \(\Rightarrow E_\gamma \leq 2.4 \text{ GeV}\)
- \(E_\gamma\) measurement by recoil electron tagging
- Tagged photon intensity = \(1 - 5 \times 10^6\) cps

\(\text{e}^-\) Beam Divergence

\(<\sigma_{x'}\> = 58 \mu\text{rad}\)
@LEPS 7.8m straight section

\(<\sigma_{x'}\> = 12 \mu\text{rad}\)
@LEPS2 30m straight section

Experimental Site (135m)

LEPS \(42m^2\) (area) \(\times\) 3m (high)

LEPS2 \(198m^2\) (area) \(\times\) 10m (high)

15 times in volume!
LEPS2/BGOegg Experimental Setup

Side Detectors for Charged Particles

Cylindrical Drift Chamber (CDC)

Inner Plastic Scintillator (IPS)

Upstream Charge Veto Counter

1.3~2.4 GeV photon beam

60 crystals × 22 layers covering 24°~144°
σ_E = 1.3% @ 1 GeV

‘Egg’-shape assembly of 1,320 BGO crystals
World highest performance at the energy region below 1 GeV

Large Acceptance Electromagnetic Calorimeter

Drift Chamber (DC)
z=1.6 m, θ<21°

Resistive Plate Chamber (RPC)
Z=12.5 m, θ<6.8°

Forward Charged Particle Detectors

Target

LH₂ (t54 mm) : 2014 Nov - Feb, 2015 Sep - Dec
Carbon (t20 mm) : 2015 Apr - July, 2016 Apr – July
Cu : 2017 May (t1.5 mm), 2018 Jan – Feb (t7.5 mm)
➢ Introduction of Spring-8 LEPS2/BGOegg experiments

➢ Baryon resonance studies via single meson photoproduction off the proton

➢ Studies of η’ mass in nuclei

➢ Near future Plan of BGOegg experiment

➢ Summary
The studies of excited baryon resonances are important for understanding the hadron structure which has not been well explained by the constituent quark model and the lattice QCD.

\( \pi^0 \) photoproduction: I=1 \( \Rightarrow \) Both \( N^* \) and \( \Delta^* \) contribute at s-channel.

👍 Traditional & Many existing data

\( \Rightarrow \) Check of analysis method & luminosity.

👍 Any hint for the discrepancy of CLAS & CBELSA \( d\sigma/d\Omega \) at low energies & backward angles.

\( \eta/\omega \) photoproduction: I=0 \( \Rightarrow \) Only couple with nucleon resonances (N*).

The \( \eta \) meson couples to \( ss \) quarks.

The N*s & \( \Delta^* \)s have broad widths overlapping with each other. The measurement of the photon beam asymmetry (\( \Sigma \)) in addition to the \( d\sigma/d\Omega \) helps to decompose the resonances with the interferences of helicity amplitudes.

\[
\sigma \propto |H_1|^2 + |H_2|^2 + |H_3|^2 + |H_4|^2 \\
\Sigma \propto Re(H_1H_4^* + H_2H_3^*)
\]

The photon beam asymmetries for \( E_\gamma \geq 2 \) GeV are very scarce for all modes.
**Analysis Procedure**

**Event Selection**
- $E_γ$ meas. (1.3—2.4 GeV) at tagger.
- 2 or 3 neutral clusters at BGOegg.
  - $π^0 → γγ$ (Br=98.8%)
  - $η → γγ$ (Br=39.4%)
  - $ω → π^0γ → γγγ$ (Br=8.40%)
- Proton detection at DC or BGOegg.

**χ² probability cut with Kinematic Fit**
- Required 4-momentum conservation & $π^0$ / $η$ mass (PDG value).
- Better S/N ratio & resolutions are expected.

**Vertex is assumed to be variable on z-axis.**

**2 or 3 neutral clusters ⇒ 4-momenta of each $γ$**

**Beam energy comes from tagger.**

**Only the proton direction is measured at DC or BGOegg.**

**π⁰**
- ~650K events

**η**
- ~56K events

**ω**
- ~37K events
Differential Cross Section of $\gamma p \rightarrow \pi^0 p$

22 energy bins for $1300 < E_\gamma < 2400$ MeV & 17 polar angle bins for $-1.0 < \cos \theta^\text{CM}_\pi < 0.7$

- ●: this work (BGOegg)
- □: CLAS [PRC76 (2007) 025211]
- ○: CBELSA [PRL94 (2005) 012003]
- △: CBELSA [PRC84 (2011) 055203]
- ◇: GRAAL [EPJA26 (2005) 399]

Note: The histogram indicates the systematic error of the BGOegg meas. Typically 4-5%.

Closer to the CLAS, GRAAL, and LEPS results than the CBELSA result at the backward & Low $E_\gamma$ region.

⇒ CLAS has claimed the $d\sigma/d\Omega$ data can be explained by “4-star” resonance states without introducing new high spin states.

Being published.
Differential Cross Section of $\gamma p \rightarrow \pi^0 p$

22 energy bins for $1300 < E_\gamma < 2400$ MeV & 17 polar angle bins for $-1.0 < \cos \theta^\text{CM}_\pi < 0.7$

More or less consistent with the existing PWA model calculations.

How about the photon beam asymmetry?
Photon Beam Asymmetry of $\gamma p \rightarrow \pi^0 p$

16 energy bins for $1300 < E_\gamma < 2400$ MeV & 16 polar angle bins for $-1.0 < \cos \theta_{CM}^\pi < 0.6$

- ●: this work (BGOegg)
- □: CLAS [PRC88 (2013) 065203]
- ○: CBELSA [PRC81 (2010) 065210]
- ◇: GRAAL [EPJA26 (2005) 399]
- ★: Daresbury [NPB104(1976)253]
- ☆: Daresbury [NPB154(1979)492]
- *: CEA [PRL28(1972)1403]

Syst. error (hist) : 0.006 – 0.050

➢ Angular behavior similar to the other experimental results at lower energies, indicating the contribution of higher spin states.
➢ A wide angle measurement at $E_\gamma \gtrsim 2$ GeV is new.

Being published.
Photon Beam Asymmetry of $\gamma p \rightarrow \pi^0 p$

16 energy bins for $1300 < E_\gamma < 2400$ MeV & 16 polar angle bins for $-1.0 < \cos \theta_{\pi}^{CM} < 0.6$

**The existing PWA models deviate at the high energies where experimental data is scarce.**

- **Bonn-Gatchina**: [https://pwa.hiskp.uni-bonn.de/BG2014_02_obs_int.htm](https://pwa.hiskp.uni-bonn.de/BG2014_02_obs_int.htm)
- **GWU SAID**: [http://gwdac.phys.gwu.edu/analysis/pr_analysis.html](http://gwdac.phys.gwu.edu/analysis/pr_analysis.html)
- **ANL-Osaka**: [Private communication with Prof. Sato (Osaka Univ.)]
Comparison with PWA results at high energy region

Photon Beam Asymmetry ($\Sigma$) at $2200 < E_\gamma < 2300$ GeV

- ○: this work (BGOegg), ⚫: LEPS [PLB657 (2007) 32], ★: Daresbury [NPB104(1976)253]

SAID PWA reproduces the backward dip structure, while the middle & forward angle range can be explained only by Bonn-Gatchina PWA. The inconsistency of two PWA models tells a large ambiguity in the amplitude solution at $E_\gamma > 2$ GeV.

- The backward dip structure comes from a higher multipole amplitude ($M_{5-}$), which has the same quantum number as high spin resonances ($H_{19}$ & $H_{39}$ with $J^P=9/2^+$).
Differential Cross Section for $\gamma p \rightarrow \eta p$

20 energy bins for $1820 < \sqrt{s} < 2320$ MeV & 16 polar angle bins for $-1.0 < \cos \theta_{\eta}^{CM} < 0.6$

$d\sigma/d\Omega$ : Closer to the CLAS result, but not well agree with the LEPS & CBELSA results at $\cos \theta > -0.7$. At the most backward region, getting closer to the CBELSA result. Variation in PWA results at backward angles because of the data inconsistencies.

Enhancement at higher energies
Photon Beam Asymmetry for $\gamma p \rightarrow \eta p$

10 energy bins for $1820 < \sqrt{s} < 2320$ MeV & 8 polar angle bins for $-1.0 < \cos \theta_{\eta}^{CM} < 0.6$

$\sum$: The angle dependence is drastically changed above 1.9 GeV.
Measurement above 2.12 GeV is new.
$\Rightarrow$ None of PWA models reproduce the BGOegg result.
Photon Beam Asymmetry for $\gamma p \rightarrow \eta p$

10 energy bins for $1820 < \sqrt{s} < 2320$ MeV & 8 polar angle bins for $-1.0 < \cos \theta^\text{CM}_{\eta} < 0.6$

**Σ**: The angle dependence is drastically changed above 1.9 GeV.
Measurement above 2.12 GeV is new.
$\Rightarrow$ None of PWA models reproduce the BGOegg result.

Our simple multipole analysis with EtaMAID indicates a contribution from a high spin resonance with $L=4$ or a $u$-channel diagram.
➢ Introduction of Spring-8 LEPS2/BGOegg experiments

➢ Baryon resonance studies via single meson photoproduction off the proton

➢ **Studies of η' mass in nuclei**

➢ Near future Plan of BGOegg experiment

➢ Summary
Studies of $\eta'$ Mass in Nucleus

Large $\eta'$ mass due to the $U_A(1)$ anomaly ⇒ A good place to examine the connection with $<q\bar{q}>$. 

Optical Potential

$-150$ MeV

$-100$ MeV

$-50$ MeV

$0$ MeV

**Nagahiro et al.**

*PRC74 (2006) 045203*

NJL : $-150$ MeV

**Sakai & Jido**

*PRC88 (2013) 064906*

Linear $\sigma$ model

$-80$ MeV

**CBELSA/TAPS**

$\eta'$A interaction

$\leq-50 / -37$ MeV

transparency ratio

**Nanova et al.**

*PLB710 (2012) 600*

sub-thr. cross section

**Nanova et al.**

*PLB727 (2013) 417*

$\eta'$N scattering length in $pp\rightarrow pp\eta'$

about $-10$ MeV

**Moskal et al.**

*PLB482 (2000) 356*

**FRS@GSI**

$^{12}C(p,d)\eta'X @ 2.5$ GeV


**PRL117 (2016) 202501**

First direct measurement, but large BG.
**η’ Mass Reduction Studies at BGOegg**

High momentum proton detection at extremely forward angles. ⇒ TOF measurement at RPC

$$\gamma^{12}C \rightarrow \eta'^{11}B + p$$

or $$\eta'^{11}C + n$$

Search for the bound state in the missing mass spectrum.

&

Nuclear absorption signal for a better S/N ratio. ⇒ $$\eta'p \rightarrow \eta p$$ (back-to-back) at BGOegg

If nuclear absorption rate is low, a simple examination of the $$\eta' \rightarrow \gamma \gamma$$ mass spectrum at BGOegg is effective.

Nagahiro’s NJL calculation

Masking \(-100\sim100\) MeV region & counting signal events after fixing the event selection.
Search for \( \eta' \) Mass Medium Modification

C target data collected in 2015

- \( \omega \) photoproduction but \( 1\gamma \) is missing at BGO egg acc. hole
- Photoproduction of \( \pi^0\pi^0, \pi^0\pi^0\pi^0, \pi^0\eta, \text{etc.} \) (Mostly \( \pi^0\pi^0 \))

Search for the medium modification signal by the fit with & without the signal function.

\( \Rightarrow \) Significance will be discussed by \( \chi^2 \) difference.
We confirmed the \( \gamma \gamma \) distributions are well expressed by a smooth BG function, expressed by \( \exp(p_0 + p_1 x + p_2 x^2) \) for multiple \( \pi^0 \) or \( \eta \) photoproduction, neutral decay modes of \( \eta' \), unphysical BGs, and their sum.
The quasi-free $\eta'$ peak is expressed by a Gaussian function, whose $\sigma$ (mass resolution) is fixed to that from a realistic MC simulation.

The consistency of mass resolution between the MC simulation and the real data is very good in the tests for $\eta \rightarrow \gamma \gamma$ and $\omega \rightarrow \pi^0 \gamma \rightarrow \gamma \gamma \gamma$ events.

![Graph showing mass resolution for $\eta \rightarrow \gamma \gamma$ and $\omega \rightarrow \pi^0 \gamma \rightarrow \gamma \gamma \gamma$ events.](image)
Fitting at High Recoil Momentum Region

$P_{\eta'} \geq 1000 \text{ MeV/c}$ for demonstration

Fit with BG components

- green: quasi-free $\eta'$
- blue: smooth BG
- purple: $\omega$ (1$\gamma$ missing)

$\chi^2$/n.d.f. = 61.8/59

$\Rightarrow$ No significant contribution from the medium modification signal.

The low momentum region is under investigation as a function of binding energy and width.

Signal functions for mass reduction are also ready by taking into account the Wood-Saxon type of the nuclear density distribution.
**η’-mesic nuclei search**

**High momentum proton** detection at extremely forward angles.  
$$\gamma^{12}\text{C} \rightarrow \eta'^{11}\text{B} + \text{p}$$  
or $$\eta'^{11}\text{C} + \text{n}$$

⇒ TOF measurement at **RPC**

Search for the bound state in the **missing mass spectrum**.  
& **Nuclear absorption** signal for a better S/N ratio.

⇒ $$\eta'\text{p} \rightarrow \eta\text{p}$$ (back-to-back)  
at **BGOegg**

If nuclear absorption rate is low, a simple examination of the $$\eta' \rightarrow \gamma\gamma$$ mass spectrum at **BGOegg** is effective.

For a quantitative comparison with the experimental result, it is important to examine the validity of the cross section in the theoretical prediction by an independent mode.  
⇒ **quasi-free η’**

Masking $$-100$$ to $$100$$ MeV region & counting signal events after fixing the event selection.

**Nagahiro’s NJL calculation**
Normalization by quasi-free $\eta'$ photoproduction

Selected $\eta' \rightarrow \gamma \gamma$ with a proton detection at RPC. Then, events at $0<\text{MM}<50$ MeV was inspected because the theoretical prediction was reliable only in this region.

2015 Carbon target data
Proton detected at RPC

265 events after the side-band subtraction

$M(\gamma \gamma)$ [MeV]

No contribution from higher orbits at
$0 < \text{MM}^{[^{12}\text{C}(\gamma,p)]} - M^{[^{11}\text{B}]} - M[\eta'] < 50$ MeV

$\text{MM}$ [MeV]

17$\pm$4.6 events
Normalization by quasi-free $\eta'$ photoproduction

Selected $\eta' \rightarrow \gamma \gamma$ with a proton detection at RPC. Then, events at $0 < MM < 50$ MeV was inspected because the theoretical prediction was reliable only in this region.


No contribution from higher orbits at $0 < MM[^{12}\text{C}(\gamma,p)] - M[^{11}\text{B}] - M[\eta'] < 50$ MeV

This normalization is very important for the comparison of experiments and theories or the discussion of upper limit for $V_0$.

By taking into account Fermi motion, 172 nb/sr for $V_0 = 100$ MeV

$\Rightarrow 67.3$ events (Need a scale of $\sim 1/4$.)
Prospects for the $\eta'$-mesic nuclei search

<table>
<thead>
<tr>
<th>Missing mass range</th>
<th>$-100&lt;\text{MM}&lt;0$ MeV</th>
<th>$0&lt;\text{MM}&lt;50$ MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>BGOegg acceptance</td>
<td>0.50</td>
<td></td>
</tr>
<tr>
<td>Branching fraction</td>
<td>0.39 ($\eta \rightarrow \gamma \gamma \times \text{Br}(\eta p)$)</td>
<td>($196\pm53 \times \text{Br}(\eta p)$) ($204\pm55 \times \text{Br}(\eta p)$)</td>
</tr>
<tr>
<td>$V_0 = 100$ MeV</td>
<td>($196\pm53 \times \text{Br}(\eta p)$)</td>
<td>($204\pm55 \times \text{Br}(\eta p)$)</td>
</tr>
</tbody>
</table>

Now the above kinematical cuts are being optimized.

Absorption of $\eta'$ at rest

⇒ Isotropic & back-to-back angular distribution. The kinetic energy of $\eta$ & $p$ is monochromatic.

$\gamma p \rightarrow \eta p$; $\eta' p \rightarrow \eta p / p p' \rightarrow p p$

$\gamma p \rightarrow \pi \eta p$; $\pi p' \rightarrow \pi p / \eta p' \rightarrow \eta p$

$\gamma p \rightarrow \pi \pi p$; $\pi p' \rightarrow \eta p$

⇒ The $\eta$ or $p$ is forward-peaked.

The latter 2 modes have an extra $\pi$. 
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➢ **Near future Plan of BGOegg experiment**

➢ Summary
Near Future Plan of BGOegg experiment

Forward DC & RPC were removed for the solenoid experiment. Instead, **Forward Gamma detector & Forward Plastic Scintillators** have been installed.

⇒ A new experiment to search for the \( \eta' \) **mass medium modification** with a Cu target.

MC simulation for \( \gamma p \rightarrow \pi^0 \pi^0 p \).

BG can be reduced to 1/10 or less.

![Graph showing data points for BGOegg only and BGOegg+FG]
Prospects with $0.5X_0$ Cu target

2017 May test run w/ Cu target

2017 May: Cu 1.5 mm ($0.1X_0$), <1 Mcps, ~1w
2018 Jan-Feb: Cu 7.5 mm ($0.5X_0$), ~1 Mcps, ~4w
Aiming larger statistics & a better mass resolution.

Toy MC generation of quasi-free $\eta'$ & polynomial BG assuming:
(1) quasi-free $\eta'$ yield of the 2017 run
(2) 1/10 BG reduction w/ FG detector
(3) 4 month run w/ 2 Mcps
⇒ Upper limit to observe a signal with $\sigma \sim 13$ MeV over the BG fluctuation.

$\sigma_{\eta'} \sim 13$ MeV/c$^2$

90% upper limit [ratio to Q-F]

Binding Energy [MeV]

M($\gamma\gamma$) [MeV]

counts/5MeV
Summary

➢ Activities of BGOegg collaboration so far

- **N* physics** with single meson photoproduction off the proton
  
  **Photon beam asymmetry at higher energies** are especially unique.

- Studies for **η’ mass reduction inside nuclei** (Carbon target)
  
  **Both medium modification & mesic nuclei** are searched for.

➢ Prospects of BGOegg experiment

- Existing LH$_2$ data : **η’ photoproduction, double meson photoproduction**

- **Cu target data w/ the new setup** : Medium modification of the η’ mass
  
  * Data collection using a liquid deuteron target (a neutron target) is suitable with the new detector setup.

  * If BGOegg is moved to **LEPS beamline**, further mesic nuclei searches are possible.
LEPS2/BGOegg Collaboration


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