Evidence for a high spin $N^*$ resonance in $\eta$ photo-production in the extremely backward angle

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Physics motivation

Missing resonance problem:

- The number of states predicted by Quark Model is too excessive

Possible answers:

- correct degrees of freedom?
- simply escaped detection?

Nearly all baryons are confirmed by $\pi N$ scattering

$$\pi + p \rightarrow X \rightarrow \pi + p$$

$=>$ We study $\gamma + p \rightarrow X \rightarrow \eta + p$ at backward angles

$$\cos \theta_{\text{cm}}^\eta < -0.9$$
Physics motivation

- Higher spin resonances appear in the higher energy area.
- In the photon-proton reaction, a decay product from high spin resonances will be enhanced in the backward angle.
- Diffraction process is small at the backward angle.
Why at backward angle?

- Helicity is limited to $|h| \leq 3/2$ in photon–proton reaction => a resonance form from photon–proton reaction can not be in the helicity state $|h| > 3/2$.

- If a resonance with $J \geq 5/2$ decays, the decay product is enhanced in the forward or backward angles.

At the backward angle, high-spin $N^*$ will dominate.
The photon beam is backward Compton scattering beam using polarized ultra violet laser, Catching recoiled electron with tagging detector

\[ E_\gamma \sim 1.3 \sim 2.4 \text{GeV} \]

Tagger rate \( \sim 2 \text{Mcps} \)

The target is Liquid Hydrogen target (LH2)
A single meson production, then decay to gamma in the final state, will be measured by BGOegg detector consisted of 1320 BGO crystals
Recoiled proton is measured by DC and RPC

Cover 24° \( \sim 144° \)

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Cover 24° \( \sim 144° \)

6/11/2019
LEPS2/BGOegg experiment in Japan

\[ \gamma + p \rightarrow \eta + p \rightarrow 2\gamma + p \]

- All final state particles were detected,
- The momentum of proton in the extremely backward angles were measured by RPC,
- Kinematic fitting analysis method.
Large acceptance EM calorimeter BGOegg

60 $Bi_4Ge_3O_{12}$ crystals x 22 layers covering $24^0 \sim 144^0$, $\sigma_E = 1.3\% @ 1 GeV$

Each BGO crystal cover $6^0$ in $(\theta, \phi)$ with $L_{crystal} = 220 mm = 20X_0$
Drift Chamber (DC)

- Is the main forward charged particle detector.
- The distance from DC to target is $z = 1.6m$, the covering angle $\theta < 21^0$
Resistive Plate Chamber (RPC)

- Covering very small angle $\theta < 6$
- 12.5m distance from the target => only proton/pion/electron can be measured
- Using ToF method with Time resolution is 50-120ps

\[ \beta \] $E_{\gamma} + m_p - E_{BGO\ egg} \ (MeV) \]

\[ p \] $\pi$ $e$ $\beta$
\( \pi^0 \) Differential cross section

In order to confirm the luminosity and the validity of the normalization factor, the differential cross section of \( \pi^0 \) was obtained.

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

Note: The histogram indicates the systematic error of the BGOegg meas.


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Differential cross section $\gamma p \rightarrow \eta p$

etaMAID2018 prediction
BGOegg result
LEPS [PhysRevC.80.052201]
CLAS [Phys.Rev. C80. 045213]

$$\frac{d\sigma}{d\Omega} = \frac{14}{\mu b/sr}$$

- $0.7 < \cos \theta^\eta_{cm} < -0.6$
- $-0.8 < \cos \theta^\eta_{cm} < -0.7$
- $-0.9 < \cos \theta^\eta_{cm} < -0.8$
- $-1 < \cos \theta^\eta_{cm} < -0.9$

6/11/2019
\( \gamma p \rightarrow \eta p \) differential cross section

\[ \frac{d\sigma}{d\Omega}(\mu b/sr) \]

\[ W(\text{MeV}) \]

-0.625 < \( \cos \theta_{cm}^\eta \) < -0.6

-0.65 < \( \cos \theta_{cm}^\eta \) < -0.625

-0.675 < \( \cos \theta_{cm}^\eta \) < -0.65

-0.7 < \( \cos \theta_{cm}^\eta \) < -0.675

\[ \Delta \cos \theta_{cm}^\eta = 0.025 \]

BGOegg Data
Eta-MAID 2018

6/11/2019
\( \gamma p \rightarrow \eta p \) differential cross section

\[ \frac{d\sigma}{d\Omega} (\mu b/sr) \]

\[ -0.725 < \cos \theta_{cm}^\eta < -0.7 \]

\[ -0.75 < \cos \theta_{cm}^\eta < -0.725 \]

\[ -0.775 < \cos \theta_{cm}^\eta < -0.75 \]

\[ -0.8 < \cos \theta_{cm}^\eta < -0.775 \]

\[ \Delta \cos \theta_{cm}^\eta = 0.025 \]

BGOegg Data
Eta-MAID 2018

6/11/2019
$\gamma p \rightarrow \eta p$ differential cross section

- $0.925 < \cos \theta^\eta_{cm} < 0.9$
- $0.95 < \cos \theta^\eta_{cm} < 0.925$
- $0.975 < \cos \theta^\eta_{cm} < 0.95$
- $1 < \cos \theta^\eta_{cm} < 0.975$

BGOegg Data
Eta-MAID 2018
Systematic error

Up-to-date exp. data in this angle is rather lacking

$\Delta \cos \theta^\eta_{cm} = 0.025$
The world experimental data at the backward angle is lacking high quality data.

The disagreement between data and prediction is an indication that there could be another source of contribution.

This contribution may come from a resonance, this resonance should have spin $\geq 5/2$ and mass around 2.23GeV.
2 resonances may match with our observation: N(2220) 9/2+ and N(2250)9/2-.

- Both with the evidence in the ηN channel is only 1-star. => our data may indicate strong couplings of the state(s) to eta meson.

- Or new high-spin state which couple to η strongly.
- Strong angular dependence above 1.9GeV,
- The angular dependence changes rapidly after 1.9GeV especially at the angle < -0.8,
- The results above 2.1GeV are new measurements

⇒ In the region where CLAS data is available, our data agree with CLAS and eta-MAID. Above 2.2GeV there is a disagreement at $\cos \theta_{cm}$ near 0
Summary

- BGOegg experiment started data taking from 2013, and the first results of eta photo-production in backward angles from a proton was presented.
- A bump structure at the energy around 2.2GeV at the angle $-1 \leq \cos^{\eta}_{CM} < -0.975$ was observed. This structure disagrees with the prediction from eta-MALD.
- The data indicate strong eta coupling of N(2220) and/or N(2250) OR existence of a new high-spin resonance.
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- The data indicate strong eta coupling of N(2220) and/or N(2250) OR existence of a new high-spin resonance.
Thank you for listening
Back up
Physics motivation

- LEPS
- CLAS
- CB-ELSA
- SAID
- ETA-MAID

Sumihama et. al.
PhysRevC.80.052201

- $\eta$: large $s\bar{s}$ & isospin 0 => $N^* \rightarrow \eta p$ will have isospin 1/2
- Small t-channel contribution at the backward angle

6/11/2019
$\gamma p \rightarrow \eta p$ differential cross section

$\frac{d\sigma}{d\Omega} (\mu b \text{ sr}^{-1})$

$-0.625 < \cos \theta_{cm}^{\eta} < -0.6$

$\frac{d\sigma}{d\Omega} (\mu b \text{ sr}^{-1})$

$-0.65 < \cos \theta_{cm}^{\eta} < -0.625$

$\frac{d\sigma}{d\Omega} (\mu b \text{ sr}^{-1})$

$-0.675 < \cos \theta_{cm}^{\eta} < -0.65$

$\frac{d\sigma}{d\Omega} (\mu b \text{ sr}^{-1})$

$-0.7 < \cos \theta_{cm}^{\eta} < -0.675$
$\gamma p \rightarrow \eta p$ differential cross section

- $-0.725 < \cos \theta^\eta_{cm} < -0.7$
- $-0.75 < \cos \theta^\eta_{cm} < -0.725$
- $-0.775 < \cos \theta^\eta_{cm} < -0.75$
- $-0.8 < \cos \theta^\eta_{cm} < -0.775$

BGOegg Data
Eta-MAID

6/11/2019
\[ \gamma p \rightarrow \eta p \] differential cross section

\[
\frac{d\sigma}{d\Omega} (\text{mb} / \text{sr})
\]

\[
-0.825 < \cos \theta_{cm}^\eta < -0.8
\]

\[
-0.85 < \cos \theta_{cm}^\eta < -0.25
\]

\[
BGO\text{egg Data}
\]

\[
E\text{ta-MAID}
\]

\[
-0.875 < \cos \theta_{cm}^\eta < -0.85
\]

\[
-0.9 < \cos \theta_{cm}^\eta < -0.875
\]

\[
\frac{d\sigma}{d\Omega} (\text{mb} / \text{sr})
\]

\[
W(\text{MeV})
\]
Differential cross section (single N* mode)

\[ \cos \theta_{cm} \]

\[ \sqrt{s} = 2200 \text{MeV} \]

\[ \frac{d\sigma}{d\Omega} (\mu b/\text{sr}) \]

\[ j = \frac{9}{2} \]
\[ j = \frac{5}{2} \]
\[ j = \frac{3}{2} \]
Differential cross section (single N* mode)

\[ \sqrt{s} = 2200 \text{MeV} \]

\[ G_{17}(2190) \]
Systematic Error

Tran Nam
## Contributions of the systematic error

<table>
<thead>
<tr>
<th>Source</th>
<th>Contribution (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptance</td>
<td>&lt;3%</td>
</tr>
<tr>
<td>Kinematic fitting</td>
<td>&lt;3%</td>
</tr>
<tr>
<td>Branching ratio</td>
<td>0.2%</td>
</tr>
<tr>
<td>Target length</td>
<td>1.3%</td>
</tr>
<tr>
<td>Transmission factor</td>
<td>&lt;3%</td>
</tr>
<tr>
<td>Background contamination</td>
<td>&lt;6.24%</td>
</tr>
</tbody>
</table>
The systematic error of acceptance

• The reason for this sizeable uncertainty is the fact that the acceptance calculation requires experiment to be simulated as detailed as possible, which certainly cannot reproduce data fully.

• To estimate the contribution from the acceptance, 2 sets of MC data were generated:
  • 1\textsuperscript{st} MC set: a distribution \textit{weighted} \textit{etaMAID} cross section
  • 2\textsuperscript{nd} MC set: a distribution \textit{weighted by real data} cross section

• The cross section obtained from the acceptances determined by 2 MC data set will then be compared.
the systematic error of acceptance

<table>
<thead>
<tr>
<th>$E_y$ (MeV)</th>
<th>$\cos \theta^\eta_{cm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_y$ (MeV)</td>
<td>-0.9875</td>
</tr>
<tr>
<td>1310</td>
<td>0.50</td>
</tr>
<tr>
<td>1410</td>
<td>-1.50</td>
</tr>
<tr>
<td>1510</td>
<td>-2.14</td>
</tr>
<tr>
<td>1610</td>
<td>-0.62</td>
</tr>
<tr>
<td>1710</td>
<td>0.49</td>
</tr>
<tr>
<td>1810</td>
<td>-1.59</td>
</tr>
<tr>
<td>1910</td>
<td>-1.28</td>
</tr>
<tr>
<td>2010</td>
<td>-0.92</td>
</tr>
<tr>
<td>2110</td>
<td>-0.80</td>
</tr>
<tr>
<td>2210</td>
<td>-1.19</td>
</tr>
<tr>
<td>2310</td>
<td>-1.62</td>
</tr>
</tbody>
</table>

The difference in % of the cross section calculated from acceptance of 2 MC data sets is shown in above table

$E_y = 2110 MeV$
The systematic error of kinematic fitting and Background contamination

As can be seen, above 0.1 or 10% confident level, the $\chi^2$ probability distribution on both data and MC are flat. Below 0.1, there is a rise in the region below 0.1 on both distributions, the reason is because of the non-Gaussian of the input resolution, in addition, background contamination on data is also possible. Both of kinematic fitting cut and background contribute to the total systematic error.
The systematic error of kinematic fitting

The mean position of the $\chi^2$ probability distribution of MC and data is compared after the cut at 10% confident level to remove the potential BG contamination in data.

The resolution input of KF on MC then was adjusted by a factor ($\pm 2\%$, $\pm 4\%$, $\pm 6\%$ ...) to obtain the mean position similar to data.

- The systematic error for the kinematic fitting is obtained after recalculating the acceptance using new resolution input on MC.

<table>
<thead>
<tr>
<th>E (MeV)</th>
<th>Mean position on data</th>
<th>Mean position on MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1410</td>
<td>0.5216</td>
<td>0.5447</td>
</tr>
<tr>
<td>1610</td>
<td>0.5438</td>
<td>0.5473</td>
</tr>
<tr>
<td>1810</td>
<td>0.5462</td>
<td>0.5475</td>
</tr>
<tr>
<td>2010</td>
<td>0.5537</td>
<td>0.5488</td>
</tr>
<tr>
<td>2210</td>
<td>0.5383</td>
<td>0.5480</td>
</tr>
</tbody>
</table>
The systematic error of kinematic fitting

The changing of the mean position as a function of % changing of resolution input.
For example: changing resolution by $\pm 2\%$, $\pm 4\%$, $\pm 6\%$ ... then plot the % of changing vs the mean position on MC $\chi^2$ probability distribution. The resolution input of KF on MC is adjusted so that the mean position is same with data.
The systematic error of kinematic fitting

<table>
<thead>
<tr>
<th>E (MeV)</th>
<th>Adjustment factor for the resolution on MC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1410</td>
<td>-7%</td>
</tr>
<tr>
<td>1610</td>
<td>-1%</td>
</tr>
<tr>
<td>1810</td>
<td>-0.6%</td>
</tr>
<tr>
<td>2010</td>
<td>+1.44%</td>
</tr>
<tr>
<td>2210</td>
<td>-2.88%</td>
</tr>
</tbody>
</table>

The % of cross section changed before and after applying new resolution

<table>
<thead>
<tr>
<th>Eg (MeV)</th>
<th>cos $\theta_{cm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-0.9875</td>
</tr>
<tr>
<td>1310</td>
<td>2.04</td>
</tr>
<tr>
<td>1410</td>
<td>2.05</td>
</tr>
<tr>
<td>1510</td>
<td>-0.11</td>
</tr>
<tr>
<td>1610</td>
<td>0.81</td>
</tr>
<tr>
<td>1710</td>
<td>0.77</td>
</tr>
<tr>
<td>1810</td>
<td>0.12</td>
</tr>
<tr>
<td>1910</td>
<td>0.06</td>
</tr>
<tr>
<td>2010</td>
<td>-0.19</td>
</tr>
<tr>
<td>2110</td>
<td>0.17</td>
</tr>
<tr>
<td>2210</td>
<td>1.63</td>
</tr>
<tr>
<td>2310</td>
<td>0.49</td>
</tr>
</tbody>
</table>
Background contamination

• BG contamination can be checked by increasing the cut point in the $\chi^2$ probability distribution from 1% -> 10% confident level cut.
• Above 10% confident level cut point on data, the distribution is flat, we assume that events with >10% confident level contain no BG.

To reduce the statistical fluctuation, the data sample was separated in 2 energy region only, $E_\gamma<1.8$ GeV and $E_\gamma>1.8$ GeV.
Background contamination

The largest difference is between 1% cut and 10% cut in the region $E_\gamma > 1800\, MeV$ (red color).

The figure on the left shows the ratio between 1% and 10% cut which is also the largest difference. The statistical errors are included.
The difference in % of different cut point compare to 1% cut point (top 2 tables) and associated statistical error (bottom 2 tables)

### Background contamination

#### $E_\gamma < 1800MeV$

<table>
<thead>
<tr>
<th>CL cut (%)</th>
<th>-0.975</th>
<th>-0.925</th>
<th>-0.875</th>
<th>-0.825</th>
<th>-0.775</th>
<th>-0.725</th>
<th>-0.675</th>
<th>-0.625</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>-0.64</td>
<td>1.02</td>
<td>-0.16</td>
<td>0.25</td>
<td>-0.84</td>
<td>-0.26</td>
<td>-0.62</td>
<td>-0.52</td>
</tr>
<tr>
<td>3</td>
<td>-0.85</td>
<td>1.32</td>
<td>-0.67</td>
<td>0.13</td>
<td>-1.35</td>
<td>-0.53</td>
<td>-1.23</td>
<td>-1.32</td>
</tr>
<tr>
<td>4</td>
<td>-0.42</td>
<td>1.08</td>
<td>-1.26</td>
<td>0.40</td>
<td>-1.51</td>
<td>-1.06</td>
<td>-1.46</td>
<td>-1.22</td>
</tr>
<tr>
<td>5</td>
<td>0.43</td>
<td>0.32</td>
<td>-1.42</td>
<td>-0.19</td>
<td>-1.96</td>
<td>-1.68</td>
<td>-1.17</td>
<td>-1.21</td>
</tr>
<tr>
<td>6</td>
<td>1.15</td>
<td>0.46</td>
<td>-1.40</td>
<td>0.39</td>
<td>-1.60</td>
<td>-2.39</td>
<td>-1.36</td>
<td>-1.60</td>
</tr>
<tr>
<td>7</td>
<td>1.85</td>
<td>0.50</td>
<td>-0.95</td>
<td>-0.33</td>
<td>-1.01</td>
<td>-2.04</td>
<td>-1.40</td>
<td>-1.19</td>
</tr>
<tr>
<td>8</td>
<td>1.33</td>
<td>0.48</td>
<td>-0.62</td>
<td>0.29</td>
<td>-1.20</td>
<td>-2.21</td>
<td>-1.54</td>
<td>-1.97</td>
</tr>
<tr>
<td>9</td>
<td>1.62</td>
<td>0.56</td>
<td>-0.80</td>
<td>0.26</td>
<td>-1.82</td>
<td>-1.87</td>
<td>-1.56</td>
<td>-1.96</td>
</tr>
<tr>
<td>10</td>
<td>1.34</td>
<td>1.41</td>
<td>-1.08</td>
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</tr>
<tr>
<td>3</td>
<td>0.72</td>
<td>0.15</td>
<td>-0.53</td>
<td>-1.09</td>
<td>-0.39</td>
<td>-0.40</td>
<td>-1.40</td>
<td>0.45</td>
</tr>
<tr>
<td>4</td>
<td>2.38</td>
<td>-0.01</td>
<td>-0.61</td>
<td>-0.95</td>
<td>-0.50</td>
<td>-0.30</td>
<td>-1.46</td>
<td>-0.57</td>
</tr>
<tr>
<td>5</td>
<td>2.37</td>
<td>0.27</td>
<td>0.14</td>
<td>-0.86</td>
<td>-1.10</td>
<td>-0.39</td>
<td>-1.78</td>
<td>-0.96</td>
</tr>
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<td>-0.73</td>
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<td>-2.53</td>
<td>-2.31</td>
</tr>
</tbody>
</table>

The difference in % of different cut point compare to 1% cut point (top 2 tables) and associated statistical error (bottom 2 tables)
Transmission factor

The reason for the energy dependence of the transmission is still uncertain.

The systematic error for this transmission factor is obtained by using different fitting function to this dependence, in this case, pol2 and linear function.

Event though the $\chi^2/\text{ndf}$ of the pol2 function is better than the linear function but since the reason of this dependence is still unknown, fitting with linear function is also reasonable.

The cross section calculated using both fitting functions is compared to check the systematic error.
Transmission factor

<table>
<thead>
<tr>
<th>Eg (MeV)</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1350</td>
<td>-1.98</td>
</tr>
<tr>
<td>1450</td>
<td>-0.96</td>
</tr>
<tr>
<td>1550</td>
<td>-0.19</td>
</tr>
<tr>
<td>1650</td>
<td>0.35</td>
</tr>
<tr>
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<tr>
<td>1850</td>
<td>0.79</td>
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<tr>
<td>1950</td>
<td>0.70</td>
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<tr>
<td>2050</td>
<td>0.41</td>
</tr>
<tr>
<td>2150</td>
<td>-0.08</td>
</tr>
<tr>
<td>2300</td>
<td>-1.18</td>
</tr>
</tbody>
</table>

The cross section difference (in %) using 2 fitting function is shown in the above table.
Other contributions

• There is an error associated with the value used for the $\eta \to 2\gamma$ decay branch, which is taken from the error determined by the experimental measurements used to produce the branching ratio PDG values. The error is 0.2%

• The length of the liquid hydrogen target used in the current experiment is 54 cm with 1% contribution to the uncertainty in the calculation of the target area density.

• The photon flux determination is relate to the deadtime of the data acquisition system, the deadtime is calculated from the scalers and assume to have insignificant contribution to the uncertainty due to high precision of the scalers.