Precision Measurement of $\eta$ Radiative Decay Width via the Primakoff Effect

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Outline

1. Physics motivation
2. How do we measure?
3. Current status
Confinement QCD

- Frontier of QCD
- Sensitive probe \rightarrow\text{symmetry test}
QCD Lagrangian in Chiral limit ($m_q \to 0$) is invariant under:

$$SU_L(3) \times SU_R(3) \times U_A(1) \times U_B(1)$$

- **Chiral symmetry** $SU_L(3) \times SU_R(3)$ spontaneously broken:
  - 8 Goldstone Bosons ($\pi, K, \eta$)
- **$U_A(1)$** is explicitly broken:
  - (Chiral anomalies)
  - $\Gamma(\pi^0 \to \gamma\gamma), \Gamma(\eta \to \gamma\gamma), \Gamma(\eta' \to \gamma\gamma)$
  - Mass of $\eta_0$
- **Massive quarks**, $SU(3)$ broken:
  - GB are massive
  - Mixing of $\pi^0, \eta, \eta'$

The $\pi^0, \eta, \eta'$ system provides a rich laboratory to study the symmetry structure of QCD at low energies.
PrimEx Program at JLab

Precision measurements of electromagnetic properties of $\pi^0$, $\eta$, $\eta'$ via Primakoff effect.

I. Two-Photon Decay Widths:
1) $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ @ 6 GeV
2) $\Gamma(\eta \rightarrow \gamma\gamma)$
3) $\Gamma(\eta' \rightarrow \gamma\gamma)$

Input to Physics:
- Test chiral symmetry and chiral anomalies
- Determine light quark mass ratio
- $\eta$-$\eta'$ mixing angle

II. Transition Form Factors at low $Q^2$ (0.001–0.5 GeV$^2$/c$^2$):
$F(\gamma\gamma^* \rightarrow \pi^0)$, $F(\gamma\gamma^* \rightarrow \eta)$, $F(\gamma\gamma^* \rightarrow \eta')$

Input to Physics:
- $\pi^0$, $\eta$ and $\eta'$ electromagnetic interaction radii
- Is $\eta'$ an approximate Goldstone boson?
- Muon $g$-2
Impact of $\Gamma(\eta \rightarrow \gamma\gamma)$ Measurement

1. Improve all decay widths in $\eta$-sector

2. Extract $\eta-\eta'$ mixing angle:

3. Determine light quark mass ratio:

$$Q^2 = \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2}, \quad \text{where } \hat{m} = \frac{1}{2}(m_u + m_d)$$

Input for Cabibbo Angle Determination

\[ V_{us} = \sin(\theta_c) \]

- Light quark masses are input to extract \( V_{us} \) from kaon decays or hyperon decays.

- \( V_{us} \) is a cornerstone for CKM unitarity test

\[ |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 \]
Primakoff Method

\[ \frac{d\sigma_{\text{Pr}}}{d\Omega} = \Gamma_{\gamma\gamma} \frac{8\alpha Z^2 \beta^3 E^4}{m_{\eta}^3 Q^4} \left| F_{\text{e.m.}}(Q) \right|^2 \sin^2 \theta_{\eta} \]

Features of Primakoff cross section:
- Peaked at very small forward angle
  \[ \langle \theta_{\text{Pr}} \rangle_{\text{peak}} \propto \frac{m^2}{2E^2} \]
- Beam energy sensitive
  \[ \left\langle \frac{d\sigma_{\text{Pr}}}{d\Omega} \right\rangle_{\text{peak}} \propto E^4, \int d\sigma_{\text{Pr}} \propto Z^2 \log(E) \]
- Coherent process

Requirement:
- Luminosity
- Beam energy
- Coherency
Primakoff Method

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Requirement:
- Luminosity
- Beam energy
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E_{\text{beam}} = 11 \text{ GeV}
\gamma + ^4\text{He} \rightarrow \eta + ^4\text{He}
Experimental Setup in Hall D

- Tagged photon beam (~9.5-11.7 GeV)
- Pair spectrometer and a TAC detector for the photon flux control
- Liquid Hydrogen (3.5% R.L.) and $^4$He targets (~4% R.L.)
- Forward Calorimeter (FCAL) detects the $\eta \rightarrow \gamma \gamma$ decay photons
- CompCal and FCAL to measure electron Compton scattering for control of overall systematics.
Experimental Challenges

Compared to $\pi^0$:

- $\eta$ mass is a factor of 4 larger
- smaller cross section
  \[
  \left< \frac{d\sigma_{Pr}}{d\Omega} \right>_{\text{peak}} \propto \frac{E^4}{m^3}
  \]
- larger overlap between Primakoff and hadronic processes:
  \[
  \left< \theta_{Pr} \right>_{\text{peak}} \propto \frac{m^2}{2E^2} \quad \left< \theta_{NC} \right>_{\text{peak}} \propto \frac{2}{E \cdot A^{1/3}}
  \]
- larger momentum transfer (coherency, form factors, FSI,...)

1. Higher beam energy
2. Light targets
Advantage of Light Targets

Low A targets to control:

- Coherency: compact nucleus
- Separate background

\[
\langle \theta_{\text{pr}} \rangle_{\text{peak}} \propto \frac{m^2}{2E^2} \quad \langle \theta_{\text{NC}} \rangle_{\text{peak}} \propto \frac{2}{E \cdot A^{1/3}}
\]

- Well known form factors

Hydrogen:

- No inelastic hadronic contribution
- No nuclear final state interactions

\(^4\text{He}:

- Higher Primakoff cross section: \( \sigma_{\text{pr}} \propto Z^2 \)
Current Status

• Recently passed the Experiment Readiness Review and is recommended for 2018 beam request.

• CompCal Calorimeter

• Liquid $^4$He target
CompCal Calorimeter

1. 96 of PWO crystal modules coupled to Hamamatsu R4125HA PMTs (from NPS in Hall C)

2. Central 2x2 crystals are removed for beam to pass through

- Engineering design is done
- Calorimeter will be ready by Aug 2018.
The existing cryotarget in Hall D with a new, two-piece heat shield:

- A 0.75 mm copper upstream of target cell
- A 0.25 mm aluminum surrounding the cell
# Beam Time

<table>
<thead>
<tr>
<th>Activity</th>
<th>Days</th>
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<tbody>
<tr>
<td>Setup calibration, checkout</td>
<td>2</td>
</tr>
<tr>
<td>Tagger efficiency, TAC runs</td>
<td>1</td>
</tr>
<tr>
<td>Liquid $^4$He target run</td>
<td>30</td>
</tr>
<tr>
<td>LH$_2$ target run</td>
<td>40</td>
</tr>
<tr>
<td>Empty target run</td>
<td>6</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>79</strong></td>
</tr>
</tbody>
</table>
Estimated Error Budget

Systematical uncertainties:

<table>
<thead>
<tr>
<th>Contributions</th>
<th>Estimated Error</th>
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<tbody>
<tr>
<td>Luminosity</td>
<td>1.2%</td>
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<tr>
<td>Background subtraction</td>
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<tr>
<td>Event selection</td>
<td>1.7%</td>
</tr>
<tr>
<td>Acceptance and misalignment</td>
<td>0.5%</td>
</tr>
<tr>
<td>Beam energy</td>
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</tr>
<tr>
<td>Detection efficiency</td>
<td>0.5%</td>
</tr>
<tr>
<td>Branching ratio (PDG)</td>
<td>0.51%</td>
</tr>
<tr>
<td><strong>Total Systematic</strong></td>
<td><strong>3.0%</strong></td>
</tr>
</tbody>
</table>

Total uncertainty:

<table>
<thead>
<tr>
<th>Statistical</th>
<th>1.0%</th>
</tr>
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<tr>
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<td>3.0%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>3.2%</strong></td>
</tr>
</tbody>
</table>
A precision measurement of $\Gamma(\eta \rightarrow \gamma \gamma)$ is developed.

Experiment is preparing to run in 2018.

Physics impact:

- Improve all decay widths in the $\eta$-sector of PDG
- Quark mass ratio
- Mixing angle of $\eta$-$\eta'$
- Input for $V_{us}$ determination and CKM unitarity test

This project is supported by NSF PHY-1506303 award.
Control Systematics with Compton Scattering $(\gamma + e \rightarrow \gamma' + e')$

CompCal is needed for systematics control:

- Luminosity
- Monitoring the experimental stability

$E_\gamma = 11$ GeV
CompCal Prototype (25 lead glass assembly)

- Lead glass (4 cm x 4 cm x 45 cm)
- FEU 84 PMT
- HyCal divider (passive)

Prototype assembly
CompCal Prototype Beam Test Result

- Measure counter rate at different distances from the beam line.
  - use the same thresholds as FCAL
  - magnetic field was turned on
  - CompCal was not calibrated

- Estimated rate of the CompCal (PWO) counter $R \leq R^{FCAL}_{INNER}$