The $\pi^0$ Lifetime Experiment
and Future Plans at JLab

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(for the PrimEx Collaboration at JLab)
• The PrimEx Experiment at JLab:
  □ Physics Motivation
  □ Previous Experiments
  □ Why do we need a New Primakoff Experiment?
  □ Summary

• The $\Gamma(\eta \rightarrow \gamma\gamma)$ Experiment at JLab:
  □ Existing World Data
  □ How to make an Improved Primakoff Experiment?
  □ Summary
• $\pi^0 \rightarrow \gamma\gamma$ decay proceeds primarily via chiral anomaly in QCD.

• The prediction of chiral anomaly is exact for massless quarks:

$$\Gamma(\pi^0 \rightarrow \gamma\gamma) = \frac{\alpha^2 m^3_\pi}{64\pi^3 F^2_\pi} = 7.725 \text{ eV}$$

where $F_\pi = 92.42 \pm 0.25$ MeV is the pion decay constant.

• Explicit breaking of chiral symmetry, induced by non-zero $u$– and $d$–quark masses, generates corrections to the chiral limit prediction.

• Corrections due to isospin breaking ($\pi^0, \eta, \eta'$ mixing) are proportional to quark mass differences.

• Recent theoretical calculations of NLO corrections in $\chi$PT predict:

$$\Gamma(\pi^0 \rightarrow \gamma\gamma) = 8.10 \text{ eV}$$

$\sim 4\%$ higher than the LO prediction, with an uncertainty of less than $1\%$.

• High precision measurements of $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ at $\sim 1\%$ level will provide ultimate test of fundamental prediction of chiral anomaly in QCD.
$\Gamma(\pi^0 \rightarrow \gamma\gamma)$ World Data

Experiments

$\pi^0 \rightarrow \gamma\gamma$ Decay Width (eV)

- DESY (Primakoff)
- CERN (Direct)
- Cornell (Primakoff)
- Tomsk (Primakoff)

Next to Leading Order, ±1%

Leading Order Chiral Anomaly
• The Direct Method:
  Mean decay length measurement

  □ Experiment at CERN SPS (1985)
  \((P_{\text{proton}} = 450 \text{ GeV}/c \Rightarrow L_{\text{mean}} \sim 50 \text{ } \mu\text{m})\)

  □ Results: \(\Gamma_{\pi^0 \rightarrow \gamma\gamma} = (7.34 \pm 0.18 \pm 0.11) \text{ eV (±3.0%)}\)

  □ Dominant systematic error:
  - uncertainty in \(P_{\pi^0}\) (±1.5%)
  (average from \(\pi^\pm\) spectra.)

• \(e^+e^-\) Collider Experiments:

  □ Experiment: DORIS II @ DESY

  □ Results: \(\Gamma_{\pi^0 \rightarrow \gamma\gamma} = (7.7 \pm 0.5 \pm 0.5) \text{ eV (±10.0%)}\)

  □ Dominant systematic errors:
  - luminosity (\(\sim 6\%\)), and
  - beam-residual gas interaction

  □ Not included in PDG average
Primačoff Effect

\[ \frac{d^3\sigma_{pr}}{d\Omega} = \Gamma_{\gamma\gamma} \frac{8\alpha Z^2}{m^3} \frac{\beta^3 E^4}{Q^4} |F_{\text{e.m.}}(Q)|^2 \sin^2 \theta \]

\[ \langle \theta_{pr} \rangle_{\text{peak}} \sim \frac{m^2}{2E^2}, \quad \int d\sigma_{pr} \sim Z^2 E^2, \quad \left( \frac{d\sigma_{pr}}{d\Omega} \right)_{\text{peak}} \sim E^4 \]

\[ \square \text{ Task: extract the Primakoff amplitude.} \]
Primakoff Experiments

- **DESY (1970)**
  - bremsstrahlung $\gamma$ beam: $E_\gamma = 1.5, 2.5$ GeV
  - targets: C, Zn, Al, Pb
  - Results: $\Gamma_{\pi^0 \rightarrow \gamma\gamma} = (11.7 \pm 1.2) \text{ eV (±10.0%)}$
  - Dominant systematic errors:
    - geometrical acceptance: ±7%
    - statistical: ±6%
    - quantameter: ±3%

- **Cornell (1974)**
  - bremsstrahlung $\gamma$ beam: $E_\gamma = 4, 6$ GeV
  - targets: Be, Al, Cu, Ag, U
  - Results: $\Gamma_{\pi^0 \rightarrow \gamma\gamma} = (7.92 \pm 0.42) \text{ eV (±6%)}$
  - Dominant systematic errors:
    - photon number: ±4%
    - quantameter: ±2%

- All experiments used:
  - Bremsstrahlung Photon Beams;
  - Conventional Lead Glass Calorimeter
- High resolution, high intensity CW JLab Photon Tagging Facility
- Pair Spectrometer (PS) to correct Tagger at high intensities
- High resolution PbWO₄ novel Hybrid Electromagnetic Calorimeter (HYCAL)
 photon flux control

- **Goal:** 1.0% in $N_{\gamma}$: $\Leftarrow$ from Tagger
- **Problem:** will run at high intensities $\sim 6 \times 10^7$ equiv. $\gamma$/sec
- **Solution:** Pair Spectrometer as on-line Photon Flux Monitor

 Photon Flux Control With Pair Spectrometer

![Photo of equipment with text](image)

### Preliminary Run

<table>
<thead>
<tr>
<th>Relative Tagging Ratio</th>
<th>$x \times 10^7$ equiv. $\gamma$/sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0031</td>
<td>1</td>
</tr>
<tr>
<td>0.0032</td>
<td>2</td>
</tr>
<tr>
<td>0.0033</td>
<td>3</td>
</tr>
<tr>
<td>0.0034</td>
<td>4</td>
</tr>
<tr>
<td>0.0035</td>
<td>5</td>
</tr>
<tr>
<td>0.0036</td>
<td>6</td>
</tr>
<tr>
<td>0.0037</td>
<td>7</td>
</tr>
</tbody>
</table>

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The HYCAL Calorimeter

Calorimeter Concept: Optimize Performance and Cost

- ~1200 PbWO₄ crystal detectors: (to enhance position and energy resolutions)
- ~600 Pb-glass detectors: (to optimize the costs)
- Detector area ~120×120 cm²
Lead glass detectors are well known.

Beam tests for PbWO₄ crystal detectors at JLab:

### Energy Resolution

<table>
<thead>
<tr>
<th>Detector Size</th>
<th>Resolution (E/E)</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1x1</td>
<td>3.4%</td>
<td>100%</td>
</tr>
<tr>
<td>3x3</td>
<td>1.6%</td>
<td>94%</td>
</tr>
<tr>
<td>6x6</td>
<td>1.3%</td>
<td>75%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Statistics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>χ²/ndf</td>
<td>86.02 / 31</td>
</tr>
<tr>
<td>Constant</td>
<td>194.4</td>
</tr>
<tr>
<td>Mean</td>
<td>4.290</td>
</tr>
<tr>
<td>Sigma</td>
<td>0.5572E-01</td>
</tr>
</tbody>
</table>

### Position Resolution

<table>
<thead>
<tr>
<th>Statistics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>χ²/ndf</td>
<td>97.13 / 52</td>
</tr>
<tr>
<td>Constant</td>
<td>86.34</td>
</tr>
<tr>
<td>Mean</td>
<td>-1.534</td>
</tr>
<tr>
<td>Sigma</td>
<td>1.288</td>
</tr>
</tbody>
</table>

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Improvements Over Previous Experiments

- Photon Flux: $N_\gamma \leftrightarrow$ from (Tagger + Pair Spectrometer)
- Invariant Mass: $M_{\gamma\gamma} \leftrightarrow$ from HYCAL
- Pion Production Angle: $\theta_\pi \leftrightarrow$ from (HYCAL + Tagger)
- Background Subtraction: $\leftrightarrow$ from (HYCAL + Tagger)
## PrimEx Error Budget

### Experimental Uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>statistical</td>
<td>0.4%</td>
</tr>
<tr>
<td>target thickness (atoms/cm$^2$)</td>
<td>0.7%</td>
</tr>
<tr>
<td>photon flux</td>
<td>1.0%</td>
</tr>
<tr>
<td>$\pi^0$ detector acceptance and misalignment</td>
<td>0.4%</td>
</tr>
<tr>
<td>background subtraction</td>
<td>0.2%</td>
</tr>
<tr>
<td>beam energy</td>
<td>0.2%</td>
</tr>
<tr>
<td>distorted form factor calculation errors</td>
<td>0.4%</td>
</tr>
<tr>
<td><strong>total</strong></td>
<td><strong>1.4%</strong></td>
</tr>
</tbody>
</table>
PrimEx Summary

• Perform 1.4% precision measurement of $\Gamma(\pi^0 \rightarrow \gamma\gamma)$.

• Test fundamental prediction of QCD – the axial anomaly.

• Check NLO corrections ($\sim 4\%$) induced by isospin breaking as predicted by $\chi$PT.

• Will significantly improve all systematic uncertainties over previous experiments:
  - high precision CW photon tagging facility in Hall B.
  - pair spectrometer for on-line photon flux control.
  - high resolution electromagnetic calorimeter (HYCAL).

• PrimEx will start January, 2004 at JLab.
Experimental Data for $\Gamma(\eta \rightarrow \gamma\gamma)$

<table>
<thead>
<tr>
<th>Experiments</th>
<th>Decay Width (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MD1 90</td>
<td>0.7</td>
</tr>
<tr>
<td>JADE 85</td>
<td>0.6</td>
</tr>
<tr>
<td>CBAL 88</td>
<td>0.5</td>
</tr>
<tr>
<td>ASP 90</td>
<td>0.4</td>
</tr>
<tr>
<td>Cornell (Primakoff)</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Proposed Exp. 0.2
Average (PDB) 0.1
Choose the Right Target $\rightarrow 4\text{He}$ and $1\text{H}$

New High Energy Photon Tagger (12 GeV JLab upgrade)

Improved Calorimetry $\rightarrow$ HYCAL with all PbWO$_4$
Improvement on $\eta-\eta'$ mixing angle

<table>
<thead>
<tr>
<th>$\eta-\eta'$ mixing angle, $\theta$ (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cornell Primakoff</td>
</tr>
<tr>
<td>PDB Average</td>
</tr>
<tr>
<td>Proposed Exp.</td>
</tr>
<tr>
<td>Collider Average</td>
</tr>
</tbody>
</table>

Experiments
Determination of Quark Mass Ratio

\[ Q^2 = \frac{M_K^2}{M^2_{\pi}} \cdot \frac{M_K^2 - M^2_{\pi}}{M_{K^0}^2 - M_{K^+}^2} (1 + O(m^2)) \]

From observed values of meson masses

⇒ tight constraint on particular ratio of quark masses:

\[ Q^2 \equiv \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2} \]

where \( \hat{m} = \frac{1}{2}(m_u + m_d) \).
Summary

• High precision (∼ 2-5%) measurements of two-photon decay widths at 12 GeV:
  - $\Gamma(\pi^0 \rightarrow \gamma\gamma)$, $\Gamma(\eta \rightarrow \gamma\gamma)$, $\Gamma(\eta' \rightarrow \gamma\gamma)$

• Crucial input for fundamental physics:
  - $(\eta - \eta')$ mixing
  - Determination of light quark mass ratio
  - Critical tests of QCD-based models

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URL: www.jlab.org/primex/