The Primakoff Experimental Program at Jefferson Lab

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Outline

• Introduction
• Current JLab Primakoff program at 6 & 12 GeV
• New opportunities with future 24 GeV upgrade
• Summary
Challenges in Physics

Confinement QCD

- Nature of QCD confinement
- Its relationship to the dynamical chiral symmetry breaking

New physics beyond the Standard Model (SM)

- New sources of CP violation
- Dark matter
- Dark energy

The Primakoff effect provides a great experimental tool to explore both fundamental issues.
What is the Primakoff Effect?

H. Primakoff, Phys. Rev. 81, 899 (1951)
**Distinguishable Features of Primakoff Effect**

\[
\frac{d\sigma_{Pr}}{d\Omega} = \Gamma \frac{8\alpha Z^2}{m^3} \frac{\beta^3 E^4}{Q^4} |F_{e.m.}(Q)|^2 \sin^2 \theta_{\pi}
\]

- Peaked at very small forward angle: \(\langle \theta_{Pr} \rangle_{peak} \propto \frac{m^2}{2E^2}\)
- Beam energy sensitive:
  \[
  \langle \frac{d\sigma_{Pr}}{d\Omega} \rangle_{peak} \propto \frac{E^4}{m^3}, \quad \int \frac{d\sigma_{Pr}}{d\Omega} \propto \frac{z^2}{m^3} \log E
  \]
  \[
  \langle O_{\text{Pr}} \rangle_{peak} \propto \frac{m^2}{2E^2}, \quad \langle O_{\text{NC}} \rangle_{peak} \propto \frac{2}{E \cdot A^{1/3}}
  \]
- Coherent process
- The higher beam energy is, the higher Primakoff cross and the better separation of Primakoff from the nuclear backgrounds.
- A higher beam energy is more important for more massive particle
Primakoff Program at JLab 6 & 12 GeV

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

a) 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:
- precision tests of chiral symmetry and anomalies
- determination of light quark mass ratio
- $\eta$-$\eta'$ mixing angle
- input to calculate HLbL in $(g-2)_\mu$

b) Transition Form Factors
at $Q^2$ of 0.001-0.3 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 the $\eta'$ an approximate Goldstone boson?
- input to calculate HLbL in $(g-2)_\mu$
Low-Energy QCD Symmetries and Light Mesons

- QCD Lagrangian in Chiral limit ($m_q \rightarrow 0$) 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 breaks to $SU(3)$
  - 8 Goldstone Bosons (GB)
- $U_A(1)$ is explicitly broken:
  - (Chiral anomalies)
  - $\Gamma(\pi^0 \rightarrow \gamma\gamma)$, $\Gamma(\eta \rightarrow \gamma\gamma)$, $\Gamma(\eta' \rightarrow \gamma\gamma)$
  - Non-zero mass of $\eta_0$
- $SU_L(3) \times SU_R(3)$ and $SU(3)$ are explicitly 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.
Status of Primakoff Program at JLab 6 & 12 GeV

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

a) 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:
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• The chiral anomaly prediction is exact for massless quarks:

$$\Gamma(\pi^0 \rightarrow \gamma\gamma) = \frac{m_{\pi^0}^3 \alpha^2 N_c^2}{576 \pi^3 F_{\pi^0}^2} = 7.750 \pm 0.016 \text{ eV}$$

• $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ is one of the few quantities in confinement region that QCD can calculate precisely at $\sim$1% level to higher orders!
Status of Primakoff Program at JLab 6 & 12 GeV (cont.)

Precision measurements of electromagnetic properties of π⁰, η, η’ via Primakoff effect

a) Two-Photon Decay Widths:
1) $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ @ 6 GeV
2) $\Gamma(\eta \rightarrow \gamma\gamma)$
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Input to Physics:
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- input to calculate HLbL in (g-2)$_\mu$

On-Going PrimEx-eta experiment

- Two data sets were collected in 2019 and in 2021.
- The third run started on Aug 18 until Dec 19, in 2022.
Physics for $\Gamma(\eta \rightarrow \gamma\gamma)$ Measurement

1. Resolve long standing discrepancy between previous collider and Primakoff measurements:

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

3. Improve calculation of the $\eta$-pole contribution to Hadronic Light-by-Light (HLbL) scattering in $(g-2)_\mu$

4. Improve all partial decay widths in the $\eta$-sector
A clean probe for quark mass ratio:

- $\eta \rightarrow 3\pi$ decays through isospin violation:
  \[ A = (m_u - m_d)A_1 + \alpha_{em}A_2 \]

- $\alpha_{em}$ is small

- Amplitude:
  \[ A(\eta \rightarrow 3\pi) = \frac{1}{Q^2} \frac{m_K^2}{m^2_\pi} (m^2_\pi - m^2_K) \frac{M(s,t,u)}{3\sqrt{3} F^2_\pi} \]

**Graph**: 
- Cornell, Primakoff
- Collider Average
- Proposed Exp.
- Lattice RM123
- Dashen Th.

**Text**: 
\[ Q^2 = \frac{m^2_s - \hat{m}^2}{m^2_d - m^2_u}, \quad \text{where} \quad \hat{m} = \frac{1}{2} (m_u + m_d) \]

**Reference**: Phys. Rept. 945 (2022) 1-105
A clean probe for quark mass ratio:

- $\eta \rightarrow 3\pi$ decays through isospin violation:
  \[ A = (m_u - m_d) A_1 + \alpha_{em} A_2 \]
- $\alpha_{em}$ is small
- Amplitude:
  \[ A(\eta \rightarrow 3\pi) = \frac{1}{Q^2} \frac{m_K^2}{m_\pi^2} (m_\pi^2 - m_K^2) \frac{M(s, t, u)}{3\sqrt{3} F_\pi^2} \]

- Critical input to extract Cabibbo Angle, $V_{us} = \sin(\theta_c)$ from kaon or hyperon decays.
- $V_{us}$ is a cornerstone for test of CKM unitarity:
  \[ |V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 \]
PrimEx-eta Experiment on $\Gamma(\eta \to \gamma\gamma)$ in Hall D

- Tagged photon beam (~8.0-11.7 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.)
- The $\eta$ decay photons are detected by Forward Calorimeter (FCAL); the charged decay particles of $\eta$ are detected by the GlueX spectrometer.
- CompCal and FCAL to measure Compton scattering off atomic electron for control of overall systematics.
Control Systematics with Compton Scattering

\[ \gamma + e \rightarrow \gamma' + e' \]

\[ \gamma + e \rightarrow \gamma' + e' \]

Be target

NLO QED prediction

\[ \sigma \text{ [mb / electron]} \]

\[ \sigma \text{ [mb / electron]} \]

\[ \text{Photon Beam Energy [GeV]} \]

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\[ \text{p}^4\text{He target} \]

NLO QED prediction
Preliminary Results on the $\eta$ Yield

$\eta$ Yield from phase I data:

\[ \gamma + {}^4\text{He} \rightarrow \eta + {}^4\text{He} \]
\[ E_\gamma: \ 8 - 11 \text{ GeV} \]

Simulations:

$\eta \rightarrow \gamma\gamma$

$\eta \rightarrow \pi^0\pi^0\pi^0$
Space-Like Transition Form Factors
\((Q^2 : 0.001-0.3 \text{ GeV}^2/c^2)\)

- Direct measurement of slopes
  - Interaction radii:
    \(F_{\gamma\gamma P}(Q^2) \approx 1 - 1/6 \cdot <r^2>_P Q^2\)
  - ChPT for large \(N_c\) predicts relation between the three slopes. Extraction of \(O(p^6)\) low-energy constant in the chiral Lagrangian

- Input for hadronic light-by-light calculations in muon (\(g-2\))

Phys.Rev.D65,073034
Improvement with a 24 GeV Beam

Higher Primakoff cross section: \[ \frac{d\sigma_{Pr}}{d\Omega}_{\text{peak}} \propto \frac{E^4}{m^3} \int d\sigma_{Pr} \propto \frac{Z^2}{m^3} \log(E) \]

Better separation of Primakoff from nuclear processes:

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

A 24 GeV beam will significantly improve the measurements of decay width \( \Gamma(\eta' \rightarrow \gamma\gamma) \), the transition form factors \( F(\eta \rightarrow \gamma\gamma) \) and \( F(\eta' \rightarrow \gamma\gamma) \).
New opportunities with JLab 24 GeV Upgrade

1. Precision measurement of decay width $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ and transition form factor $F(\pi^0 \rightarrow \gamma^*\gamma)$ via the Primakoff effect off an atomic electron target.

2. Search for new sub-GeV gauge bosons (scalars and pseudoscalars) via the Primakoff production:
   - Strong CP and Hierarchy problems
   - $(g - 2)_\mu$ and puzzle of proton charge radius
   - Portals coupling SM to the dark sector:

\[
H^+ H (\epsilon S + \lambda S^2) \quad c_{\gamma\gamma} \frac{\alpha}{4\pi} \frac{a}{f} F_{\mu\nu} \tilde{F}^{\mu\nu} + c_{GG} \frac{\alpha_s}{4\pi} \frac{a}{f} G_{\mu\nu} \tilde{G}^{a,\mu\nu}
\]
Advantages of the $\pi^0$ Primakoff Production off an Electron

PrimEx-II: $\gamma + ^{28}\text{Si} \rightarrow \pi^0 + ^{28}\text{Si}$

Advantages of an electron target:
- Eliminate all nuclear backgrounds
- Point-like target
- Recoiled electron detection

Main challenges for the nuclear target:
- Nuclear backgrounds
- Nuclear charge form factor
- No recoil detection

Measurement | Reaction | $E_{th}$ (GeV)
--- | --- | ---
$\Gamma(\pi^0 \rightarrow \gamma\gamma)$ | $\gamma + e \rightarrow \pi^0 + e$ | 18.0
$F(\pi^0 \rightarrow \gamma^*\gamma)$ | $e + e \rightarrow \pi^0 + e + e$ | 18.1

$E_\gamma$: 4.45-5.30 GeV

$E_\gamma^\text{beam} = 24$ GeV

$E_\gamma$: 20-23 GeV

$\frac{d\sigma_{Pr}}{d\Omega} = \Gamma_{\gamma\gamma} \frac{8\alpha Z^2}{m_{\pi}^3} \frac{\beta^3 E^4}{Q^4} |F_{\text{e.m.}}(Q)|^2 \sin^2 \theta_{\pi}$
BSM Physics in Dark Sector

- New gauge forces, bosons and fermions beyond SM.
- The stability of dark matter can be explained by the dark charge conservation.
Where to Search for Dark Matter?

Sub-GeV region represents a good discovery opportunity.
Motivation for sub-GeV New Physics

If these anomalies are interpreted in terms of new physics, all point to new forces with mediator particles in the MeV–GeV mass range!
Search for New Scalar and Pseudoscalar via Primakoff Effect

\[ \mathcal{L}_{\text{eff}} \supset \frac{c_\gamma}{4 \Lambda} a F^{\mu \nu} \tilde{F}_{\mu \nu} \]

\[ \frac{d\sigma_{Pr}}{d\Omega} \sim \frac{c_\gamma^2 \alpha Z^2}{8 \pi \Lambda^2} \cdot \frac{\beta^3 E^4}{Q^4} \cdot |F_{\text{e.m.}}(Q)|^2 \sin^2 \theta_a \]

The Primakoff signal dominates in the forward angles

Favorable experimental condition:

- A high energy beam
- A high Z nuclear target

Minimizing the QCD backgrounds

PrimEx I
Summary

- The distinguishable features of Primakoff effect make it a great experimental tool for SM tests and BSM physics searches.

- The current JLab Primakoff program at 6&12 GeV has been in progress. The published PrimEx result on the $\pi^0$ lifetime provides a stringent test of low-energy QCD. The future 24 GeV beam will greatly improve measurements of more massive particles, such as $\eta'$.

- A 24 GeV beam will offer new opportunities for the Primakoff physics:
  - New generation of Primakoff experiments on $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ and $F(\pi^0 \rightarrow \gamma^*\gamma)$ off an electron target.
  - Search for new sub-GeV gauge bosons (scalars and pseudoscalars).

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