Primakoff Production and Ultraperipheral Processes with an e-p Collider

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Outline

- What is the Primakoff Effect?
- Current Primakoff Experimental Program at Jlab
- Expansion of Primakoff Program with e-p Collider
- Beyond Primakoff effect with e-p Collider
- Summary
What is the Primakoff Effect?

Photo-Production of Neutral Mesons in Nuclear Electric Fields and the Mean Life of the Neutral Meson*

H. Primakoff†
Laboratory for Nuclear Science and Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts
January 2, 1951

It has now been well established experimentally that neutral \( \pi \)-mesons \( (\pi^0) \) decay into two photons.\(^1\) Theoretically, this two-photon type of decay implies zero \( \pi^0 \) spin;\(^2\) in addition, the decay has been interpreted as proceeding through the mechanism of the creation and subsequent radiative recombination of a virtual proton-anti-proton pair.\(^3\) Whatever the actual mechanism of the (two-photon) decay, its mere existence implies an effective interaction between the \( \pi^0 \) wave field, \( \varphi \), and the electromagnetic wave field, \( E, H \), representable in the form:

Interaction Energy Density \( = \eta (\hbar/\mu c)(\hbar c)^{-1} \varphi \mathbf{E} \cdot \mathbf{H} \). (1)

Here \( \varphi \) has been assumed pseudoscalar, the factors \( \hbar/\mu c \) and \( (\hbar c)^{-1} \) are introduced for dimensional reasons (\( \mu \) \( \equiv \) rest mass of \( \pi^0 \)),

H. Primakoff, Phys. Rev. 81, 899 (1951)

Features of Primakoff Effect

- Production cross section is peaked at extremely small \( t \)
- Coherent process
- Beam energy sensitive

\[
\langle \theta_{\text{Pr}} \rangle_{\text{peak}} \propto \frac{m^2}{2E^2} \left( \frac{d\sigma_{\text{Pr}}}{d\Omega} \right)_{\text{peak}} \propto E^4, \int d\sigma_{\text{Pr}} \propto Z^2 \log(E)
\]
PrimEx Project at Jlab 6&12 GeV

Experimental program

Precision measurements of:

a) Two-Photon Decay Widths:

1) \( \Gamma(\pi^0 \rightarrow \gamma \gamma) @ 6 \text{ GeV} \)
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

b) Transition Form Factors at low \( Q^2 (0.001 - 0.5 \text{ GeV}^2/c^2) \):
\( F(\gamma\gamma^* \rightarrow \pi^0), F(\gamma\gamma^* \rightarrow \eta), F(\gamma\gamma^* \rightarrow \eta') \)

Input to Physics:

- \( \pi^0, \eta \) and \( \eta' \) interaction electromagnetic radii
- is the \( \eta' \) an approximate Goldstone boson?
Symmetries in QCD

- Classical QCD Lagrangian in Chiral limit 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)
  - \( \Gamma(\pi^0 \rightarrow \gamma \gamma), \Gamma(\eta \rightarrow \gamma \gamma), \Gamma(\eta' \rightarrow \gamma \gamma) \)
  - 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.
Status of PrimEx at JLab

- PrimEx-I Experiment in Hall B for $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ was approved in 1999 and reapproved in 2002.
  - The experiment performed in 2004 with 6 GeV beam.
  - Publication is in progress.

- PrimEx-II for $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ was approved by PAC33 in Jan 2008, is under preparation to run in Hall B with 6 GeV.

- The 12 GeV part of program has was reviewed by 3 special high energy PACs. Included in Jlab 12 GeV upgrade White paper and CDR.
  - PAC18 (2000)
  - PAC23 (2003)
  - PAC27 (2005)

- The first 12 GeV Primakoff experiment on $\Gamma(\eta \rightarrow \gamma\gamma)$ in Hall D was recently approved by PAC35 in Jan 2010.
First Jlab Primakoff Experiment: $\pi^0$ Lifetime

- $\pi^0 \rightarrow \gamma\gamma$ decay proceeds primarily via the chiral anomaly in QCD.
- The chiral anomaly prediction is exact for massless quarks:
  \[
  \Gamma(\pi^0 \rightarrow \gamma\gamma) = \frac{\alpha^2 N_c^2 m_{\pi}^3}{576 \pi^3 F_{\pi}^2} = 7.725 \text{ eV}
  \]

- $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ is one of the few quantities in confinement region that QCD can calculate precisely at higher orders!
  - Corrections to the chiral anomaly prediction:
    - (u-d quark masses and mass differences)
    - Calculations in NLO ChPT:
      - $\Gamma(\pi^0 \rightarrow \gamma\gamma) = 8.10 \text{ eV} \pm 1.0\%$
      - $\Gamma(\pi^0 \rightarrow \gamma\gamma) = 8.09 \text{ eV} \pm 1.3\%$
  - Calculations in QCD sum rule:
      1. $\Gamma(\eta \rightarrow \gamma\gamma)$ is the only input parameter
      2. $\pi^0$-$\eta$ mixing included
    - $\Gamma(\pi^0 \rightarrow \gamma\gamma) = 7.93 \text{ eV} \pm 1.5\%$

- Precision measurements of $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ at the percent level will provide a stringent test of a fundamental prediction of QCD.
Primakoff Method

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

\[
\left\langle \theta_{Pr} \right\rangle_{peak} \propto \frac{m^2_\pi}{2E^2}, \quad \left( \frac{d\sigma_{Pr}}{d\Omega} \right)_{peak} \propto E^4, \quad \int d\sigma_{Pr} \propto Z^2 \log(E)
\]

Extract the Primakoff amplitude based on different angular dependences

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March 15, 2010
Experiment on $\Gamma(\pi^0 \to \gamma\gamma)$ at 6 GeV

- JLab Hall B high resolution, high intensity photon tagging facility

- New pair spectrometer for photon flux control at high intensities

- New high resolution hybrid multi-channel calorimeter
PrimEx-I Experiment: $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ Decay Width

- Nuclear targets: $^{12}\text{C}$ and $^{208}\text{Pb}$;
- $6$ GeV Hall B tagged beam;
- experiment performed in 2004
PrimEx-I Result, New PrimEx-II Experiment

Control of Overall Systematical errors:
Compton Cross Section Measurement

PrimEx-I
\( \Gamma(\pi \rightarrow \gamma\gamma) = 7.82 \text{eV} \pm 2.2\% \pm 2.1\% \)

PrimEx-II projected \( \pm 1.4\% \)

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Measurement of $\Gamma(\eta\rightarrow\gamma\gamma)$ in Hall D at 12 GeV

- We propose to use GlueX standard setup for this measurement:

- Photon beam line - Incoherent tagged photons
- Pair spectrometer
- Solenoid detectors (for background rejection)
- 30 cm LH2 and LHe4 targets (~3.6% r.l.)
- Forward tracking detectors (for background rejection)
- Forward Calorimeter (FCAL) for $\eta\rightarrow\gamma\gamma$ decay photons
- Add CompCal detector for overall control of systematics
Physics Outcome from New $\eta \rightarrow \gamma \gamma$ Experiment

- **Light quark mass ratio:**
  
  $\eta \rightarrow 3\pi$ **forbidden** by isospin symmetry, therefore:

  \[ \Gamma(\eta \rightarrow 3\pi) \propto A^2 \propto Q^{-4} \quad \text{with:} \]

  \[ Q^2 = \frac{m_{\pi}^2 - m_{\pi}^2}{m_{d}^2 - m_{u}^2}, \quad \text{where } \hat{m} = \frac{1}{2}(m_{u} + m_{d}) \]

  \[ \Gamma(\eta \rightarrow 3\pi) = \Gamma(\eta \rightarrow \gamma \gamma) \times \text{BR}(3\pi)/\text{BR}(\gamma \gamma) \]

- **(\eta - \eta') mixing angle:**

  \[ (m_{K^0} - m_{K^+})_{\text{c.m. Corr.}} \]

  H. Leutwyler PLB, 378,1996

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**Challenges in \( \eta \rightarrow \gamma\gamma \) Experiment**

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

- **Difficulties of \( \eta \rightarrow \gamma\gamma \) experiment:**
  - \( \eta \) mass factor of 4 larger than \( \pi^0 \);
  - cross section is smaller;
  - larger overlap between Primakoff and hadronic processes;
  - larger momentum transfer:
    (coherency, form factors, FSI,..)

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

**Challenge:** Separate Primakoff amplitude from hadronic processes.

We propose to use LH2 and LHe4 targets to address all those issues.

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\( \gamma + ^4\text{He} \rightarrow \eta + ^4\text{He} \)

Cross Section \( d\sigma/d\Omega \) (mb/\text{sr})

\( E_{\text{beam}} = 11 \text{ GeV} \)
Advantages of the Proposed Targets

- Precision measurements require low A targets to control:
  - coherency
  - contributions from nuclear processes

- Hydrogen:
  - no inelastic hadronic contribution
  - no nuclear final state interactions
  - proton form factor is well known
  - better separation between Primakoff and nuclear processes
  - new theoretical developments of Regge description of hadronic processes


- $^4$He:
  - higher Primakoff cross section
  - the most compact nucleus
  - form factor well known
  - new theoretical developments for FSI

Estimated Error Budget

Systematical errors:
(added quadratically)

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Total estimated error:
(added quadratically)

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Transition Form Factors of $\pi^0$, $\eta$ and $\eta'$ at Low $Q^2$

$Q^2 (0.001-0.5 \text{ GeV}^2/c^2)$

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

- Test different models
- Test of future lattice calculations

China, 2009

Liping Gan, UNCW
Transition Form Factors

Previous Experiments: Time-like region

- Dalitz decay of mesons: \( P \rightarrow \gamma e^+ e^- \)

Problems:
- small kinematical range;
- significant background;
- large rad. Corrections;
- low statistics

\[
F_{\gamma^* \gamma^* \pi^0}(0, Q^2) = F_{\gamma^* \gamma^* \pi^0}(0, 0)(1 - a_\pi Q^2/m_\pi^2)
\]

Results:
\[ a_\pi = [-0.24 \text{ to } +0.12] \]
Collision experiments: $e^+e^- \rightarrow e^+e^- P$
only one lepton detected to control $Q^2$

Experiments: CELLO @ PETRA
at $Q^2 = 0.62 - 2.17 \text{ (GeV/c)}^2$

Results (from VMD fit):

$a_\pi = 0.0325 \pm 0.0026$
Transition Form Factors
Previous Experiments: Space-like region

- Collider experiments: $e^+e^- \rightarrow e^+ e^- P$
  - only one lepton detected to control $Q^2$

Experiments: CELLO @ PETRA
at $Q^2 = 0.62 - 2.17 \text{(GeV/c)}^2$

Results (from VMD fit):

$a_\eta = 0.428 \pm 0.063$

Also for $\eta'$:

$a_{\eta'} = 1.46 \pm 0.16$
Transition Form Factors: Primakoff Method


Use electro-Primakoff method to measure transition form factors.

\[ \frac{d^3 \sigma}{d\epsilon_2 d\Omega_2 d\Omega_P} = \frac{Z^2 \eta^2}{\pi} \frac{q_P^4}{k^4} \frac{\beta^{-1}}{\omega_P} \left| F_N(K^2) \right|^2 \left| F_{\gamma^* \gamma P^0} (q_\mu^2) \right|^2 \sin^2 \frac{\theta_e}{2} \sin^2 \theta_P \]

\[ \times \left[ 4 \epsilon_1 \epsilon_2 \sin^2 \phi_P + |q|^2 / \cos^2 \frac{\theta_e}{2} \right] \]

\[ \eta^2 = \left( \frac{4}{\pi m^3} \right)/\tau \quad \text{with } \tau \text{ is the life time of meson} \]

\[ \left< \theta_{Pr} \right>_{peak} \propto \frac{-k^2 + m^2}{2E_\pi^2} \quad \left< \theta_{NC} \right>_{peak} \propto \frac{2}{E_\pi \cdot A^{1/3}} \]

Electro-Primakoff cross section is peaked at relatively larger angle than real photon Primakoff

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Primakoff Method: Sensitivity to Slope Parameter

\[ a_\pi = 0.1 \]

\[ a_\pi = 0.03 \]

\[ ^4\text{He} \]
Primakoff Production with an e-p Collider

- A high energy electron beam on a proton target. For a 5-10 GeV electron and 30-60 GeV proton collider, it is equivalent to a 320-1279 GeV electron beam on the proton at rest.

- Differences between Primakoff productions @ e-p collider and $\gamma*\gamma*$ reaction @ e+e- Collider

- Primakoff cross section is peaked forward along the beam line. Its phase space is different from other production processes in lab frame.
- Decay products from light particles are energetic in the lab frame.
- The mesons are produced at rest in the lab frame. The phase space for different processes are overlap in lab frame.
- Decay products from light particles have relatively low energies.
Advantages of High Energy e-p Collider

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

- Better separation of Primakoff reaction from nuclear processes:
  \[
  \langle \theta_{Pr} \rangle_{\text{peak}} \propto \frac{m^2}{2E^2} \quad \langle \theta_{NC} \rangle_{\text{peak}} \propto \frac{2}{E \cdot A^{1/3}}
  \]

- Primakoff cross section is peaked at extremely small t can serve as a nature kinematic filter

- Polarized virtual photons and polarized protons

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Primakoff Program with e-p Collider

- Benefit for $\Gamma(\eta' \rightarrow \gamma\gamma)$ measurement with higher beam energy
- Benefit for the transition form factors $F(\eta \rightarrow \gamma^*\gamma)$ and $F(\eta' \rightarrow \gamma^*\gamma)$
- Expand the current PrimEx program to include more heavier mesons, such as $f_0(980)$, $f_2(1270)$, $a_2(1320)$, $f_0(1370)$
  - Radiative decay widths $\Gamma(\gamma\gamma)$
  - Transition form factors $F(\gamma\gamma^* \rightarrow p)$
Hadron Polarizabilities

- Study hadron polarizabilities by $\gamma \gamma \rightarrow pp$ reaction, $P$ represents $\pi, \eta$, and other mesons.

- Hadron electric and magnetic polarizabilities characterize the induced transient dipole moments of hadron subjected to external electromagnetic fields. For $t \rightarrow 0$,

$$\left(\frac{d\sigma}{d\Omega}\right)_{\gamma\gamma \rightarrow \pi^0\pi^0}^{\chi PT} = \frac{1}{2} \frac{m^2}{4} \frac{\beta_\gamma \pi}{2} |\bar{\alpha}_{\pi^0}^* (s)|^2 s \quad \bar{\alpha}_{\pi^0} \approx \bar{\alpha}_{\pi^0} \left(1 - \frac{13}{15} \frac{t}{m^2} - \frac{1}{4} \frac{t}{m_k^2}\right)$$

where $\bar{\alpha}_{\pi^0} = -\bar{\beta}_{\pi^0}$

- The Primakoff cross section for two pion production is

$$\frac{d^2\sigma}{d\Omega dE_{\pi\pi}} = \frac{\alpha Z^2}{\pi^2} \sigma(\gamma \gamma \rightarrow \pi\pi) \frac{\beta^2 E^4}{E_{\pi\pi}^2 Q^4} |F(Q)|^2 \sin^2 \theta_{\pi\pi} K_{\pi}$$

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Neutral Axial Coupling of Proton

- Axial coupling is $G_A = \Delta u - \Delta d - \Delta s$
- For circularly polarized photons:
  $$A^\gamma \equiv \frac{d\sigma(h = +) - d\sigma(h = -)}{d\sigma(h = +) + d\sigma(h = -)}$$
  $$\approx \frac{1 - 4s_w^2 G_F (-t)}{4\pi \sqrt{2} \alpha} G_A G_M \frac{t - m_n^2}{G_E^2 - \frac{1}{4M^2} G_M^2} 2ME$$

- For longitudinally polarized protons:
  $$A^p \equiv \frac{d\sigma(s = +) - d\sigma(s = -)}{d\sigma(s = +) + d\sigma(s = -)}$$
  $$\approx \frac{1 - 4s_w^2 G_F (-q^2)}{4\pi \sqrt{2} \alpha} G_A G_E \frac{G_A G_E}{G_E^2 - \frac{q^2}{4M^2} G_M^2}$$

- The neutral vector coupling of the proton is filtered out in the Primakoff effect and only $G_A$ is left in the observables.
Beyond Primakoff: Study QCD symmetries via $\eta$ and $\eta'$ Rare Decays

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<th>Branching Ratio</th>
<th>Physics Highlight</th>
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<td>$\pi^0 \pi^0$</td>
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<td>CP, P</td>
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<td>$\pi^0 2\gamma$</td>
<td>$(2.7 \pm 0.5) \times 10^{-4}$</td>
<td>$\chi^{PTh}, O(p^6)$</td>
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History of the $\eta \rightarrow \pi^0 \gamma \gamma$ Measurements

A long standing “$\eta$” puzzle is still un-settled

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High Energy $\eta$ Production
GAMS Experiment at Serpukhov

- Experimental result was first published in 1981
- The $\eta$'s were produced with 30 GeV/c $\pi^-$ beam in the $\pi^-p\rightarrow\eta n$ reaction
- Decay $\gamma$'s were detected by lead-

Final result:
$\Gamma(\eta\rightarrow\pi^0\gamma\gamma) = 0.84 \pm 0.17$ eV
Low energy $\eta$ production

CB experiment at AGS


- The $\eta$'s were produced with 720 MeV/c $\pi^-$ beam through the $\pi^-p \rightarrow \eta n$ reaction
- Decay $\gamma$'s energy range: 50-500 MeV

Final result:
$$\Gamma(\eta \rightarrow \pi^0 \gamma\gamma) = 0.285 \pm 0.031 \pm 0.061 \text{ eV}$$
What can be improved with e-p collider

- **High energy electro-production** $e + p \rightarrow e' + \eta + p$ to reduce the background from $\eta \rightarrow 3\pi^0$
  - Lower relative threshold for $\gamma$-ray detection
  - Improve calorimeter resolution
- **High resolution, high granularity Calorimeter**
  - Higher energy resolution → improve $\pi^0\gamma\gamma$ invariance mass
  - Higher granularity → better position resolution and less overlap clusters
- **Large statistics** to provide a precision measurement of Dalitz plot

\[ E_\pi = 30 \text{ GeV/c} \]

\[ E_\pi = 720 \text{ MeV/c} \quad \phi \text{ production } \sqrt{s} = 1020 \text{ MeV} \]

\[ \phi \rightarrow \gamma\eta \]
Summary

• Benefit and expand the current existing PrimEx program on radiative decay width and transition form factor measurements.

• Access hadron polarizabilities via double meson Primakoff productions

• Measurement of the **Neutral Axial Coupling of Proton** via the parity violating asymmetries in the Primakoff production for longitudinally polarized protons

• Test QCD symmetries and search for new physics beyond standard model via $\eta$ and $\eta'$ Rare Decays
The End