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PI0 DECAY

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■ **Abstract** The study of π^0 decay has played an important role in the development of particle physics: The $\pi^0 \to \gamma\gamma$ decay provides key insights into the anomaly sector of quantum chromodynamics. In this review, the historical progression of π^0 discovery, lifetime measurements, and theory are presented. A new measurement of the π^0 radiative width via the Primakoff effect has been made at Jefferson Laboratory. The result $\Gamma(\pi^0 \to \gamma\gamma) = 7.82 \pm 0.14$ (stat.) $\pm$ 0.17 (sys.) eV is a factor of 2.1 more precise than the currently accepted value, and it is in agreement with the chiral anomaly prediction and with next-to-leading-order chiral perturbation theory calculations. Primakoff experiments at higher energies to measure the η and η' radiative widths are also discussed.

Keywords pion radiative width, Primakoff effect**[**AU: Deleted because keyword cannot form part of article title, per house style**]**

1. INTRODUCTION

[AU: Given that the π^0 particle is referred to in the text either as "π^0" or as "neutral pion", consider changing title to "Neutral Pion Decay"?*]**The neutral pion (π^0) enjoys a special status in the family of elementary particles; it is the lightest strongly interacting particle observed in nature. Therefore, the underlying symmetries of quantum chromodynamics (QCD) are especially relevant in predicting properties of π^0 decay. The QCD symmetry of importance for π^0 decay is chiral symmetry, which occurs in the limit of massless u and d quarks (1, pp. 157–87). In this limit, effective field theories of QCD are highly predictive, and the predicted rate for $\pi^0 \to \gamma\gamma$ is given by

$$\Gamma\left(\pi^0 \to \gamma\gamma\right) = \frac{\alpha^2 m_\pi^3}{576\pi^3 F_\pi^2} N_C^2 = 7.73 \text{ eV}, \quad 1.$$

where α is the fine-structure constant, m_π is the π^0 mass, F_π is the pion decay constant, and $N_C = 3$ is the number of QCD colors. This prediction is remarkable because it contains no unknown low-energy constants or form factors and is in agreement with the currently accepted value for the radiative width, 7.74 ± 0.46 eV (2), which confirms $N_C = 3$ as the number of QCD colors.

The prediction for $\Gamma(\pi^0 \to \gamma\gamma)$ given in **Equation 1** is exact in the chiral limit, that is, when the u and d quark masses vanish. Corrections arise because the physical (current) quark masses are not zero; $m_u \approx 4$ MeV and $m_d \approx 7$ MeV. The next-to-leading-order (NLO) theoretical predictions for the $\pi^0 \to \gamma\gamma$ decay width are completely untested because of the low precision of existing measurements. A precision measurement of the π^0 lifetime, $\tau_{\pi 0}$, ranks as one of the definitive low-energy tests of QCD.

The discovery of the π^0 was an important milestone in the development of experimental particle physics; the π^0 was the first particle to be discovered with an accelerator. In this review, the historical progression of the particle's discovery, its lifetime measurement, and theory are presented. The centerpiece of this review is a discussion of the PrimEx experiment, which is a precision measurement of the π^0 radiative width (3). The PrimEx experiment established another notable milestone by measuring absolute photoproduction cross sections to an accuracy of ~1%, thereby obtaining a measurement of $\Gamma(\pi^0 \to \gamma\gamma)$ with statistical and systematic uncertainties of 1.8% and 2.2%, respectively.

2. DISCOVERY OF THE NEUTRAL PION

The history of the discovery of π^0 reaches back to investigators' earliest efforts to connect what was known empirically about the nucleon-nucleon force to a rigorous model based on quantum theory. In 1935, Yukawa (4) postulated that nuclear forces can be ascribed to the exchange of a massive scalar particle that couples to both protons and neutrons. Shortly thereafter, scattering experiments by Tuve et al. (5) showed that the force between two protons is approximately equal to the force between a proton and a neutron. Based on this observation, Yukawa et al. (6) and Kemmer (7) extended the mesotron theory of nuclear forces to include a neutral particle with mass and properties similar to those of the charged meson. Sakata & Tanikawa (8) suggested that the neutral meson should decay to photons through the emission and annihilation of a virtual proton-antiproton pair, and their estimate of $\tau_{\pi 0} \sim 10^{-16}$ s is remarkably close to the presently accepted value of $(8.4 \pm 0.5) \times 10^{-17}$ s (2).

The first experimental hint of the π^0 was observed in the mixed cosmic ray showers observed by Chao (9) and Fretter (10), where γ rays were observed in association with meson showers. Oppenheimer and his collaborators (11) suggested that a natural interpretation for the mixed showers could be the photodecay of neutral mesons produced when high-energy protons hit the top of the atmosphere.

The neutral pion was discovered in 1950 at the Berkeley synchrocyclotron by Bjorklund et al. (12), who measured the yield of γ rays for protons incident on several nuclear targets. These authors' data indicated the opening of a channel for the emission of ~70-MeV photons at an incident proton energy of approximately 290 MeV. They concluded that these data are consistent with the decay of a neutral meson into two photons, with a meson mass approximately 300 times the electron mass.

The first lower limit on $\tau_{\pi 0}$ came from measurements of $K_{2\pi}^+$ decay at rest in nuclear emulsions, where $K^+ \to \pi^+\pi^0$ was followed by the Dalitz decay of the π^0, $\pi^0 \to e^+e^-\gamma$. In these analyses, the distance between the intersection of the K^+–π^+ tracks to the intersection of the e^+–e^- tracks was measured to find the distance traveled by the π^0 before decay (see Reference 13 for a review of the early π^0 lifetime experiments). All of the emulsion experiments were limited by a lack of events, as well as by the ability to resolve the detached e^+–e^- vertex.

Shortly after the discovery of the π^0, Primakoff (14) suggested an indirect method to measure $\tau_{\pi 0}$ by the photoproduction of π^0s at forward angles in the Coulomb field of a heavy nucleus. **Figure 1** is a diagram of the Primakoff reaction. At high incident energies and very forward angles, the coherent $\gamma A \to \pi^0 A$ cross section is dominated by the Primakoff process, which is proportional to the π^0 radiative width $\Gamma(\pi^0 \to \gamma\gamma)$,

<COMP: PLEASE INSERT FIGURE 1 HERE>

Figure 1 Schematic diagram of the Primakoff reaction.

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$$\frac{\mathrm{d}\sigma_P}{\mathrm{d}\Omega} = \Gamma\left(\pi^0 \to \gamma\gamma\right)\frac{8\alpha Z^2}{m_\pi^3}\frac{\beta^3 E_\gamma^4}{Q^4}\left|F_{EM}\left(Q^2\right)\right|^2 \sin^2\theta_\pi, \qquad 2.$$

where Z is the atomic number of the target nucleus; m_π, β, and θ_π are the mass, velocity, and lab angle of the pion, respectively; Q is the four-momentum transfer to the nucleus; and $F_{EM}(Q)$ is the nuclear electromagnetic form factor corrected for final-state interactions (FSI) of the outgoing pion. The radiative width Γ is related to $\tau_{\pi 0}$ through $\Gamma = B\hbar/\tau_{\pi 0}$, where B is the branching fraction into the two-photon final state; B is currently known with an uncertainty of ±0.034% (2).

The first successful measurement of $\tau_{\pi 0}$ via the Primakoff effect was by Bellettini et al. (13), who used a 1-GeV bremsstrahlung beam on a lead target and a 10-channel electromagnetic calorimeter. The lifetime they obtained, $(0.73 \pm 0.11) \times 10^{-16}$ s, was the most precise measurement available at that time, and it agrees with the currently accepted value (2).

3. THEORY OF NEUTRAL PION DECAY

The π^0 lifetime measurements made in the 1960s put the current-algebra theory techniques of that time to a severe test. On the basis of considerations required by Lorentz invariance, parity conservation, and gauge invariance, the π^0 radiative width is given by

$$\Gamma\left(\pi^0 \rightarrow \gamma\gamma\right) = \frac{m_\pi^3}{64\pi}\left|A_{\gamma\gamma}\right|^2. \qquad 3.$$

Working in the soft-pion limit of the partially conserved axial current (PCAC), Sutherland (15) and Veltman (16) found that $A_{\gamma\gamma} = 0$, implying that the π^0 should be stable against electromagnetic decays. Electromagnetic decay can occur at order m_π^2, but there would be a strong suppression of the decay of order $\left(m_\pi^2/1\ \text{GeV}^2\right)^2 \cong 3\times10^{-4}$ (1, pp. 181–83).

Adler (18) and Bell & Jackiw (19) found a solution to this paradox when they discovered a class of anomalous triangle diagrams with axial-vector vertices that completely altered the PCAC predictions for $\pi^0 \rightarrow \gamma\gamma$ decay. These diagrams are anomalous because the divergence of the axial-vector current is not given by the expression found in classical QCD, and so the axial-vector current does not satisfy the canonicalWard identity. Working in the soft-pion limit of PCAC, Adler found that $A_{\gamma\gamma} = \alpha/(\pi F_\pi)$, where F_π is the charged-pion decay constant; this finding is in good agreement with the experimental value.

Anomalies occur in theories when a symmetry of the classical action is not a true symmetry of the full quantum theory (1, pp. 75–77). The relevant broken symmetry for π^0 decay is exhibited by the most general order-four chiral Lagrangian given by Gasser & Leutwyler (21, 22). This Lagrangian is invariant under the transformation $U \rightarrow U^\dagger$, where U is the Goldstone boson field operator (23). The symmetry $U \rightarrow U^\dagger$ is not a symmetry of QCD, and it would forbid a known process such as $K^+K^- \rightarrow 3\pi$ from occurring (24). For this reason, it is necessary to augment the order-four chiral Lagrangian with the Wess-Zumino-Witten (WZW) anomaly term (24, 25). The remarkable properties of the WZW Lagrangian are that it contains no low-energy constants and that it is not renormalized by radiative corrections (26). The chiral anomaly (e.g., the WZW anomaly) allows transitions between even and odd numbers of the pseudoscalar mesons to occur, for example $\pi^0 \to \gamma\gamma$ and $\gamma\pi \to \pi\pi$. The chiral anomaly prediction for the $\pi^0 \to \gamma\gamma$ amplitude,

$$A_{\gamma\gamma} = \frac{\alpha N_C}{3\pi F_\pi}, \qquad 4.$$

where, as above, $N_C = 3$ is the number of QCD colors, is widely recognized as an important test of QCD, confirming the symmetries and anomalies of the theory as well as the number of colors. The predicted radiative width is $\Gamma(\pi^0 \to \gamma\gamma) = 7.724 \pm 0.044$ eV.

Recently, Bar & Wiese (27) pointed out that in the $1/N_C$ QCD expansion the quark charges depend on N_C; therefore, the amplitude $A_{\gamma\gamma}$ does not depend on N_C. On this basis, the authors conclude that π^0 decay cannot be used to determine N_C. However, the quark charges are known from many sources of information, and arguably the $1/N_C$ QCD expansion should be reserved for handling strong interaction effects, which means keeping quark charges fixed (J. Goity, personal communication). If the values of the quark charges are held fixed, then $\pi^0 \to \gamma\gamma$ decay does indeed determine $N_C = 3$.

The chiral anomaly prediction (**Equation 4**) is exact in the chiral limit in which the u and d quark masses vanish. However, the current quark masses are nonvanishing and are approximately $m_u \sim 4$ MeV, and $m_d \sim 7$ MeV. The most important correction to $\Gamma(\pi^0 \to \gamma\gamma)$ is from isospin symmetry breaking, $m_u \neq m_d$, which causes a mixing of the $U(3)$ states η and η' into the physical π^0 state (28). As a result of this state mixing, the decay amplitudes and decay constants also mix. Goity et al. (28) evaluated the π^0 decay width in a combined framework of chiral perturbation theory (ChPT) and the $1/N_C$ expansion up to $O(p^6)$ and $O(p^4 \times 1/N_C)$ in the decay amplitude, explicitly including the η'. They found that the decay width is enhanced by approximately 4.5% from the chiral anomaly result; the enhancement is almost entirely due to η and η' mixing effects. The result of this NLO analysis is $\Gamma(\pi^0 \rightarrow \gamma\gamma) = 8.10$ eV, with an estimated uncertainty of less than 1%.

In a complementary ChPT approach, Kampf & Moussallam (29) calculated NLO corrections to the π^0 radiative width from all one- and two-loop diagrams in the two-flavor (u, d) chiral expansion. This result was matched to the three-flavor chiral expansion, implicitly assuming the strange quark is sufficiently small that a chiral expansion in m_s is meaningful. This calculation also predicted that the dominant corrections to the width are from state mixing. The predicted width is $\Gamma(\pi^0 \rightarrow \gamma\gamma) = (8.09 \pm 0.11)$ eV.

Corrections to the chiral anomaly prediction have also been performed in the framework of QCD through the use of dispersion relations and sum rules, but without inclusion of the η' (30). The result obtained is $\Gamma(\pi^0 \rightarrow \gamma\gamma) = 7.93$ eV, with an estimated error of 1.5%. The three ChPT predictions for $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ (chiral anomaly, the Goity et al. results, and the Kampf & Moussallam results), as well as the QCD sum rule prediction, are shown in **Figure 2**.

<COMP: PLEASE INSERT FIGURE 2 HERE>

Figure 2 Differential cross section as a function of π^0 production angle for ^{12}C, together with the fit for Primakoff (*red dashed curve*), nuclear-coherent (*blue dashed-dotted curve*), interference (*green dotted curve*), and nuclear-incoherent (*solid blue curve*) processes, along with the total sum (*black*).

4. PREVIOUS MEASUREMENTS OF THE NEUTRAL PION LIFETIME

The Particle Data Group (PDG) bases its π^0 lifetime average on five measurements. Three are Primakoff experiments (31, 32, 33), the fourth is a direct measurement of $\tau_{\pi 0}$ (34), and the fifth is obtained from a measurement of the weak form factor F_V in the radiative pion decay $\pi^+ \rightarrow e^+ \upsilon\gamma$ (35).

4.1. Primakoff Measurements

Figure 3 shows a calculation for π^0 photoproduction at ~5 GeV for a light nucleus, ^{12}C. At very forward angles, $\theta_\pi < 0.1°$, the cross section is dominated by Primakoff production. The Primakoff peak reaches a maximum at an angle of approximately $m_\pi^2/(2E_\gamma^2)$, and has an energy dependency at the cross section peak of E_γ^4. At wide angles, $\theta_\pi > 0.5°$, the nuclear-coherent process dominates the cross section, and at intermediate angles, a Primakoff-coherent interference term contributes to the cross section because both processes have identical final states. At angles of 1.0° or more, nuclear-incoherent production becomes important; the residual nuclear excitation, $E_x < 200$ MeV (36), is typically less than the experimental energy resolution.

<COMP: PLEASE INSERT FIGURE 3 HERE>

Figure 3 Differential cross section as a function of π^0 production angle for ^{208}Pb. The curves have the same meaning as those in Figure 2.

Figure 4 shows the comparable calculation for a heavy nucleus, ^{208}Pb. Because of the rapid fall-off of the ^{208}Pb strong nuclear form factor at increasing angles, coherent π^0 photoproduction is highly suppressed in ^{208}Pb relative to ^{12}C.

<COMP: PLEASE INSERT FIGURE 4 HERE>

Figure 4 Measurements and calculations for $\Gamma(\pi^0 \rightarrow \gamma\gamma)$. Previous Primakoff experiments (31, 32, 33, 37) are labeled 1, 2, 3, and 4, respectively. The CERN direct measurement (34) is labeled 5. The PIBETA π^+ radiative decay measurement (35) is labeled 6. The DESY collider measurement (39) is labeled 7. The next-to-leading-order chiral perturbation theory (NLO ChPT) calculations (28, 29) are labeled 8 and 9, respectively. The quantum chromodynamics (QCD) sum rule calculation (30) is labeled 10. The PrimEx result (3) is labeled 11. The chiral anomaly prediction is represented by the solid red line.

The Primakoff experiments fit their differential cross sections with an equation of the form

$$\frac{d\sigma}{d\Omega} = \left|\sqrt{C_P}T_P + \sqrt{C_{NC}}e^{i\phi}T_S\right|^2 + C_{NI}\frac{d\sigma_{NI}}{d\Omega}, \qquad 5.$$

where T_P and T_S are the Primakoff and strong coherent amplitudes, respectively; φ is the phase angle between the amplitudes; and $d\sigma_{NI}/d\Omega$ is the nuclear-incoherent cross section. T_P is given by Equation 8, and nuclear reaction models were utilized to calculate T_S and $d\sigma_{NI}/d\Omega$. The constants C_P, C_{NC}, C_{NI}, and φ are fit to the data.

All three Primakoff experiments in the PDG average used untagged bremsstrahlung; the photon end-point energy at Tomsk was 1.1 GeV (31), 2.0

GeV for DESY (32), and 6.6 GeV for Cornell University (33). As a consequence of the use of untagged bremsstrahlung, the energy of the photon initiating the event was unknown, and timing cuts could not be used to reject backgrounds. The nuclear targets used in the experiments ranged from Z = 6 to Z = 92. The DESY and Cornell experiments used lead-glass Cherenkov counters to detect π^0 decay photons; the Tomsk experiment used spark chambers with photographic readout yielding 60,000 photos for analysis. The radiative widths measured at Tomsk, DESY, and Cornell are 7.23 ± 0.55 eV, 11.7 ± 1.2 eV, and 7.92 ± 0.42 eV, respectively.

A Primakoff experiment not included in the PDG average was performed at DESY. This experiment utilized a proton target and a 5.8-GeV bremsstrahlung beam (37). The data from this experiment are described further below.**[**AU: Text changed so that figures do not have to be renumbered in order of appearance---OK?**]** The advantage of this measurement over the nuclear Primakoff experiments is that the nuclear-incoherent process does not contribute. The radiative width obtained from this measurement is $\Gamma(\pi^0 \rightarrow \gamma\gamma) = 8.44 \pm 0.93$ eV.

4.2. Direct Measurement

The fourth measurement in the PDG average is a direct measurement, $\tau_{\pi 0}$, where π^0s are produced by 450-GeV/c protons incident on a target consisting of two 70-μm-thick tungsten foils (34). The π^0 decays were observed by detecting 150-GeV positrons created by the conversion of π^0 decay photons **[**AU: Edits to this sentence correct?**]**in the target foils. The foils were mounted on a stage so that the separation could be varied between 5 μm and 250 μm. The absolute scale of displacement was measured with a neon-helium laser interferometer; the stability and reproducibility of the foil position were ±0.1 μm.

If the π^0 decay length is larger (smaller) than the distance between the foils, then the positron rate is minimized (maximized). For π^0s of definite momentum, the positron rate depends on the separation of the foils (d) and the mean decay length (λ) as

$$R = N\left[\mathrm{A} + B\left(1 - e^{-d/\lambda}\right)\right]. \qquad 6.$$

The constant A accounts for the yield of positrons that do not depend on the foil separation, for example, Dalitz decays of the π^0, and conversion of the decay photon in the same foil in which the π^0 was produced in. The ratio of B to A was measured as 0.07.**[**AU: Necessary to define *B*, *N*?**]** Because the analysis is based on ratios of yields at known displacements of the foils, it is not necessary to know N, A, B, the ratio of B to A, or d. To minimize the uncertainty from the unmeasured π^0 momentum distribution, the π^0 distribution was taken as the arithmetic mean of measured π^+ and π^- distributions produced by 450-GeV protons incident on a 400-µm gold target. Atherton et al. (34) obtained a value of $\Gamma(\pi^0 \rightarrow \gamma\gamma) = 7.25 \pm 0.18 \pm 0.14$ eV, in which the errors are statistical and systematic, respectively.

4.3. Lifetime from Radiative π^+ Decay

The newest experiment in the PDG average for $\tau_{\pi 0}$ is from a measurement of the weak vector form factor F_V, which was measured in 65,460 $\pi^+ \rightarrow e^+\upsilon_\varepsilon\gamma$ events through use of the PIBETA detector (35). In this analysis, the conserved vector current hypothesis is used to relate F_V to $\tau_{\pi 0}$ (38). The result obtained for the radiative width is 7.65±0.99 eV.

4.4. Collider Measurement

Another measurement not included in the PDG average is the untagged two-photon result $e^+e^- \rightarrow e^+e^-\pi^0$; this measurement was performed by use of the Crystal Ball detector on the DORIS II storage ring at DESY (39), in which the scattered e^+e^- are undetected. This experiment has an advantage over the Primakoff measurements in that there is no nuclear background. However, the drawback to this technique is the small size of the data sample: approximately 1,000 events. The π^0 radiative width obtained from this analysis is $7.7 \pm 0.5 \pm 0.5$ eV.

Figure 4 shows $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ for the five experiments included in the PDG average, the DESY Primakoff result with the proton target, and the collider result. The scatter of the experimental data points; the small model errors in the NLO ChPT predictions; and the availability of a multi-GeV high-intensity, high-resolution, tagged-photon beam at the Thomas Jefferson National Accelerator Facility (JLab) argue for staging a new Primakoff measurement at JLab with a high-resolution electromagnetic calorimeter.

5. NEW MEASUREMENT OF THE NEUTRAL PION LIFETIME AT JEFFERSON LABORATORY

A new Primakoff experiment (PrimEx) to measure the π^0 radiative width (3) was performed in the fall of 2004 at JLab using the Hall B high-precision photon-tagging facility (40). A schematic diagram of the experiment layout is shown in **Figure 5**. To produce tagged photons, the 5.765-GeV, ~100-nA electron beam was passed through a gold radiator with a thickness of $\sim 10^{-4}$ radiation length. Electrons that lose energy are detected in the photon tagger, which is essentially a momentum-analyzing electron spectrometer. The energy of the tagged photons ranged from approximately 4.9 to 5.5 GeV, and the tagging rate was approximately 10^7 photons per second. A 12.7-mm collimator and a 0.73-T permanent sweep magnet downstream of the tagger were used to define the position of the beam and to remove charged particles produced in the collimator.

<COMP: PLEASE INSERT FIGURE 5 HERE>

Figure 5 Layout of the PrimEx experimental setup. Abbreviations: HYCAL, hybrid multichannel electromagnetic calorimeter; PS, pair spectrometer.

The targets used in the experiment were ^{12}C and ^{208}Pb, both of which had thicknesses of approximately 5% radiation length. The carbon target was machined from a block of natural isotopic highly ordered pyrolitic graphite; its approximate dimensions were $2.4 \times 2.4 \times 1.0$ cm^3. The ^{208}Pb target was a 1-inch-diameter circular foil, with a thickness of approximately 12 mil, made from 99.09% enriched ^{208}Pb. The effective number of ^{12}C and ^{208}Pb scattering centers in the targets for Primakoff production was determined to uncertainties of ±0.050% and ±0.43%, respectively (41).

Because of the extreme requirements for beam stability, a pair spectrometer (PS) was installed on the JLab Hall B beam line just downstream of the π^0 production target. This PS allowed for continuous monitoring of relative photon-tagging efficiencies by detection of the e^+e^- pairs coming from the target. The PS was constructed with a large-aperture dipole magnet run at 0.73 T·m, which is sufficient to sweep pairs created in the target outside the acceptance of the π^0 calorimeter and into the beam-left and beam-right arms of the PS. Each arm of the PS has two rows (front and back) of scintillator hodoscopes, with eight counters in each row. The absolute tagged-photon flux for the experiment was determined with an uncertainty of 1%, which is unprecedented for a tagged-photon experiment (42).

An array of 12 plastic scintillators mounted on the front face of the electromagnetic calorimeter was used to veto charged particles. The largest charged-particle background came from Compton $\gamma e \rightarrow \gamma e$ events produced in the helium bag downstream of the PS. Each veto counter has dimensions of $120\times10\times0.5$ cm^3, with phototubes mounted on the two ends. The charged-particle detection efficiency was measured by reducing the PS field so that the $e+e-$ pairs produced in the target were swept across the midplane of the veto counters; the measured efficiency was close to 100%. Of greater importance is the rejection efficiency for coherent π^0s, which is determined by measuring the yield of coherent π^0s produced at angles greater than 2°, wherein the charged-particle background is absent, with and without veto cut; the measured rejection efficiency was approximately 0.8%.

A hybrid multichannel electromagnetic calorimeter (HYCAL) was constructed to detect photons from π^0 decay (43). HYCAL uses two types of detector elements: (*a*) 1,152 $PbWO_4$ crystals in the central part of the detector, with dimensions of $2.05\times2.05\times18.0$ cm^3, surrounded by (*b*) 576 lead-glass Cherenkov counters (Schott type F-1) with dimensions of $3.82\times3.82\times45.0$ cm^3. A diagram of the HYCAL detector layout is shown in **Figure 6**. The transverse dimensions of the detector modules were designed to roughly equal the Molière radii for the detector elements---2.2 cm for $PbWO_4$ and 4.7 cm for the lead glass---so that energy leakage into adjacent counters could be used to determine the position of the shower axis.

<COMP: PLEASE INSERT FIGURE 6 HERE>

Figure 6 Hybrid multichannel electromagnetic calorimeter (HYCAL) segmentation geometry. The lead glass detectors are shown in blue. In the center, shown in red, is the 34×34 array of $PbWO_4$ channels.

The HYCAL was positioned 7.5 m downstream from the target, which provided approximately 70% geometric acceptance for Primakoff π^0s. The central 2×2 crystals were removed to allow for passage of the incident photon beam. In general, π^0s from the Primakoff peak interact in the central $PbWO_4$ region of the HYCAL. Wide-angle pions from the nuclear-coherent and -incoherent processes interact either with one decay photon in the crystal region and one in the lead-glass region of the HYCAL or with both decay photons in the lead-glass region of the HYCAL. The position of the HYCAL relative to the photon-beam axis was determined through use of atomic Compton scattering, and the planar distributions of π^0 production angles. The misalignment of the HYCAL was less than 0.4 mm throughout the data-taking process.

The HYCAL energy calibration was performed in two ways. The first calibration was done with a so-called snake scan performed at the very beginning of the experiment. In this scan, the HYCAL was moved so that every crystal and lead-glass detector element passed through a low-intensity tagged-photon beam. The snake scan was repeated at the end of the experiment. The second calibration technique is based on the $\pi^0 \rightarrow \gamma\gamma$ invariant mass constraint. There was an improvement of approximately 15% in invariant mass resolution after the recalibration using the mass-constraint technique was applied.

The HYCAL electronics were configured so that an analog sum of all the photomultiplier signals from the $PbWO_4$ and lead glass became available. The threshold on the analog energy sum was set at approximately 2 GeV. Data acquisition was triggered by a coincidence between the HYCAL and the photon tagger.

5.1. Electromagnetic Calibration Reactions

Because the goal of the experiment**[**AU: Specifically, the PrimEx experiment?**]** was to obtain absolute cross sections at the 1% level, it was essential to measure calibration reactions with the HYCAL that could be calculated to a comparable precision. Only purely electromagnetic processes can be calculated to this level of precision by use of quantum electrodynamics (QED). During the PrimEx experiment, e^+e^- pair production and atomic Compton scattering were measured.

For the measurement of pair-production cross sections, special runs were staged in which the PS magnet was reduced to approximately 0.293 T·m and the beam current to ~1 nA. The residual PS magnetic field swept e^+e^- pairs along a horizontal axis into the HYCAL. **Figure 7** shows e^- production cross sections differential in the energy fraction **[**AU: Should this read "…cross sections that are differential…"? If not, please clarify**]**$x = E_e/E_\gamma$, integrated over the spectrum of tagged photons (42). Also shown is the theoretical calculation by Krochin (44). This calculation greatly extends the Bethe-Heitler theory of pair production and includes the following amplitudes listed in order of decreasing importance: (*a*) Bethe-Heitler pair production on the nucleus with atomic screening, (*b*) pair production on atomic electrons, (*c*) QED radiative corrections of order α/π with respect to the dominant Bethe-Heitler term, (*d*) nuclear-incoherent production on protons, and (*e*) virtual Compton scattering: $\gamma A \rightarrow \gamma^* A \rightarrow e^+e^-A$. The integrated experimental and theoretical cross sections agree within the experimental errors of ±0.58 (stat.) ± 1.13 (sys.).

<COMP: PLEASE INSERT FIGURE 7 HERE>

Figure 7 Differential cross sections for pair production extracted on the electron arm of the pair spectrometer.

The second QED process utilized to ensure the stability of the experimental setup was atomic Compton scattering, in which the Compton-scattered photon and the recoil electron are detected in the HYCAL. Special Compton scattering runs were staged during the experiment; the PS magnetic field was reduced to zero so that the Compton-scattered electrons would reach HYCAL.

There are two types of radiative corrections to the lowest-order QED diagrams for Compton scattering (45). The first type is due to virtual photon loops and soft-photon emission (46). The second type alters the kinematics of Compton scattering and leads to two hard photons in the final state (47, 48). If the experimental resolution were vanishingly small, then it would be possible to reject the two-photon Compton events. However, due to finite experimental resolution, a fraction of the double Compton events are accepted as single Compton events. A Monte Carlo simulation of the experiment was used to perform the radiative corrections, and the corrected cross sections are shown in **Figure 8** for $E_\gamma = 4.92$ GeV. Also shown is the Klein-Nishina calculation (45). The agreement between experiment and theory is within the estimated ±1.5% systematic uncertainty in the cross sections. In summary, the experimental data for pair production and Compton scattering are in very good agreement with theory, and they give a useful measure of the stability of the experimental setup.

<COMP: PLEASE INSERT FIGURE 8 HERE>

Figure 8 Differential cross sections for Compton scattering, corrected for acceptance and radiative effects at $E_\gamma = 4.920$ GeV. The solid curve represents the Klein-Nishina calculation (45).

5.2. Cross Sections for Coherent Neutral Pion Photoproduction

Figure 9 shows a scatter plot for events with at least two photons in HYCAL. **[**AU: Material duplicative of figure caption removed per house style**]**The intensity peak at $\varepsilon = 1$ and $M_{\gamma\gamma} = 135$ MeV (where ε refers to elasticity and $M_{\gamma\gamma}$ to the two-photon invariant mass) is from coherent π^0 events, which include Primakoff and nuclear-coherent production. The line of π^0 events extending to elasticities $\varepsilon < 1$ is from final states with multiple mesons. The line of elastic events $\varepsilon = 1$, with $M_{\gamma\gamma} < 135$, is from elastic backgrounds, such as atomic Compton scattering.

<COMP: PLEASE INSERT FIGURE 9 HERE>

Figure 9 Scatter plot of events with at least two photon in a hybrid multichannel electromagnetic calorimeter. The vertical axis is elasticity, $\varepsilon = (E_1 + E_2)/E_\gamma$. The horizontal axis is the two-photon invariant mass, $M_{\gamma\gamma}$.

The π^0 lifetime analysis was performed by two independent analysis groups (Analyses I and II). Although these groups operated independently, they shared many of the same event-reconstruction software and simulation tools for the photon tagger and the HYCAL; they also shared photon-flux measurements (42). However, each group developed its own event-selection criteria and lists of runs to use in the analysis, as well as its own analysis and simulation tools.

To find the yield of elastic π^0s, Analysis I formed $M_{\gamma\gamma}$ distributions for events within an allowed window in elasticity centered at $\varepsilon = 1$ for each bin in θ_π. The $M_{\gamma\gamma}$ distributions were then fit with peak and background shapes, and a correction was applied to account for inelastic π^0s in the $M_{\gamma\gamma}$ peak. The corrected yield was taken as coherent π^0 production for that θ_π bin, and the analysis was repeated for each θ_π bin. Typical distributions for ε and $M_{\gamma\gamma}$ are in shown **Figure 10**.

<COMP: PLEASE INSERT FIGURE 10 HERE>

Figure 10 (*a*) Typical distributions of reconstructed elasticity, ε, and (*b*) the two-photon invariant mass, $M_{\gamma\gamma}$, for one angular bin.

Analysis II used kinematic fitting, in which cluster pairs within an allowed window in elasticity were analyzed with the constraint $\varepsilon = 1$; in other words, the events were constrained to be elastic. The corrected cluster energies in HYCAL, E_{1C} and E_{2C}, are given by the constraint equations

$$\left|\frac{E_1 - E_{1C}}{E_2 - E_{2C}}\right| = \frac{\sigma(E_1)}{\sigma(E_2)} \qquad \text{7a.}$$

and

$$E_{1C} + E_{2C} = E_\gamma\,, \qquad \text{7b.}$$

where $\sigma(E_1)$ and $\sigma(E_2)$ are the known energy resolutions for clusters one and 2. Application of this constraint yielded an improvement in π^0 mass resolution greater than 1.5. Elastic yields were found by forming $M_{\gamma\gamma}$ distributions with the elastic constraint for each bin in θ_π, then fitting these distributions with a peak and background shape.

Analyses I and II corrected their data for the contamination of events from ω production, where $\omega \rightarrow \pi^0\gamma$. In kinematics, where the photon goes backward and carries little energy, π^0s from $\omega \rightarrow \pi^0\gamma$ can contaminate the coherent π^0 production. Subtracting this physics background changed the extracted π^0 decay width by 1.4%, with an uncertainty of 0.25%. The differential cross sections for coherent π^0 photoproduction on ^{12}C and ^{208}Pb are shown in **Figures 2** and **3**, respectively.

6. RESULTS FOR THE NEUTRAL PION LIFETIME MEASUREMENT

As shown in **Equation 5**, three dynamical quantities are needed to describe π^0 photoproduction cross sections at high energies and forward angles on a nucleus: (*a*) the Primakoff (Coulomb) amplitude T_P, in which the electromagnetic form factor includes the effects of FSI of the π^0 with the nucleus; (*b*) the strong coherent amplitude T_S corrected for photon shadowing (49) and FSI; and (*c*) the nuclear-incoherent cross section $d\sigma_{NI}/d\Omega$, also corrected for photon shadowing and FSI. Motivated by the PrimEx experiment, new theoretical calculations for these amplitudes and cross sections have been developed.

6.1. Primakoff Amplitude

The Primakoff amplitude T_P is given by (50, 51)

$$T_P = Z\sqrt{8\alpha\Gamma}\left(\frac{\beta}{m_\pi}\right)^{3/2}\frac{k^2\sin\theta}{q^2+\Delta^2}F_{EM}(q,\Delta), \qquad 8.$$

where Z is the nuclear charge; Γ is the $\pi^0 \rightarrow \gamma\gamma$ radiative width; β is the velocity of the pion; k is the incident photon momentum; and q and Δ are the transverse and longitudinal momentum transfers to the nucleus, respectively. Gevorkyan et al. (52) evaluated $F_{EM}(q,\Delta)$ in the framework of Glauber multiple-scattering theory in the optical limit by using nuclear charge densities parameterized by Fourier-Bessel analyses of electron scattering data (53, 54). This approach is known to be valid for extended nuclear matter, namely medium and heavy nuclei, but it is less accurate for light nuclei. To check the validity of the ^{12}C result, Gevorkyan et al. developed an expression for $F_{EM}(q,\Delta)$ that is suitable for light nuclei by using Glauber multiple-scattering theory and shell-model harmonic-oscillator wave functions. In the region of the ^{12}C Primakoff peak, the difference between the two calculations is negligible.

6.2. Strong Coherent Amplitude

The strong coherent amplitude T_S, corrected for photon shadowing, can be written in factorized form (52):

$$T_S(q) = \vec{h} \cdot \vec{q}\,\Phi(0)\left[F_{st}(q,\Delta) - wF_I(q,\Delta_\rho)\right] \quad 9.$$

where Φ is the elementary photoproduction amplitude at forward angles, $\vec{h} = \vec{k} \times \vec{\varepsilon}/k$, and $\vec{\varepsilon}$ is the photon polarization. As $\theta_\pi \to 0$, then $\vec{q} \to 0$, and the strong coherent amplitude vanishes. In this equation, $F_{st}(q,\Delta)$ is the strong nuclear form factor; $F_I(q,\Delta_\rho)$ is the ρ intermediate channel contribution to the strong form factor from photon shadowing; w is the shadowing parameter; and $\Delta\rho$ is the longitudinal momentum transfer for ρ meson photoproduction off the nucleon, $\Delta_\rho = m_\rho^2/2E$. The shadowing parameter w can vary between zero (no shadowing) and one (vector meson--dominance model).

Gevorkyan et al. (52) calculated both $F_{st}(q,\Delta)$ and $F_I(q,\Delta_\rho)$ for ^{12}C and ^{208}Pb by using Glauber multiple-scattering theory. The calculation of $F_{st}(q,\Delta)$ includes the Fäldt correction (51), in which pions produced in the coherent process at a nonzero angle come to the forward direction following FSI. To check their result for ^{12}C, these authors also calculated $F_{st}(q,\Delta)$ and $F_I(q,\Delta_\rho)$ in multiple-scattering theory by using harmonic-oscillator wave functions. In the Primakoff peak region, the result with harmonic-oscillator wave functions is approximately 5% larger than the result with optical model approximation. These results are in acceptable agreement, given the small size of the coherent cross section relative to the Primakoff. Beyond approximately 1°, the calculations are nearly identical.

6.3. Incoherent Cross Section

Mesons can also be produced in the strong nuclear field incoherently through the reaction $\gamma A_i \rightarrow \pi^0 A_f$, where A_f includes all possible nuclear excitations and nuclear breakup reactions. For the incoherent contribution to the cross section, two new theoretical approaches were utilized in the analysis of the data. The first approach is a multicollisional Monte Carlo (MCMC) intranuclear cascade model (36). The MCMC calculations for $d^2\sigma/d\Omega dE_\pi$ show that at forward angles and photon energies $E_\gamma \sim 5$ GeV, cross-section strength is concentrated at values of nuclear excitation $E_x < 200$ MeV---less than the experimental energy resolution. For the fitting of experiment angular distributions, the MCMC calculation was integrated over this range of nuclear excitation.

The second theoretical technique used for calculating the incoherent cross section is based on Glauber multiple-scattering theory (55). Gevorkyan et al. calculated analytical expressions, including the effects of meson absorption and Pauli suppression, for the incoherent cross section based on the assumption of forward-going pions. The nuclear ground state for ^{12}C was described by the independent particle model, with harmonic-oscillator wave functions. An analytical expression for the summed coherent and incoherent cross section can be obtained by summing over a complete set of nuclear final states with nuclear excitations up to approximately 100 MeV.

6.4. Data Fitting and Results

The experimental differential cross sections shown in **Figures 2** and **3** were fit with the following equation,

$$\frac{d\sigma}{d\Omega} = C_P \frac{d\sigma_P}{d\Omega} + C_{NC} \frac{d\sigma_S}{d\Omega} + 2\cos\phi \sqrt{C_P C_{NC} \frac{d\sigma_P}{d\Omega} \frac{d\sigma_S}{d\Omega}} + C_{NI} \frac{d\sigma_{NI}}{d\Omega}, \qquad 10.$$

where $d\sigma_P/d\Omega$ is given by **Equation 2** and $d\sigma_S/d\Omega$ and $d\sigma_{NI}/d\Omega$ are the nuclear-coherent and -incoherent cross sections, respectively. The angle φ is the phase angle between the Primakoff (Coulomb) and strong coherent amplitudes. The experimental

π^0 angular resolution ($\sigma_\theta = 0.6$ mrad) was folded with the theoretical angular distribution.

The four parameters C_P, C_{NC}, C_{NI}, and φ in **Equation 10** were varied to fit the experimental differential cross sections shown in **Figures 2** and **3**. $\Gamma(\pi^0 \to \gamma\gamma)$ is obtained from the fit for C_P. The data fitting for $\Gamma(\pi^0 \to \gamma\gamma)$ was performed separately for the two targets. There was also a combined fit in which C_{NC}, C_{NI}, and φ were allowed to vary independently for the ^{12}C and ^{208}Pb angular distributions, but C_P was constrained to be the same for both targets. Table 1 shows the parameters resulting from these fits; the values for $\Gamma(\pi^0 \to \gamma\gamma)$ are weighted averages of Analyses I and II. The fitted angular distributions are shown in **Figures 2** and **3**. The final results for the radiative width are 7.79 ± 0.18 eV from ^{12}C, 7.85 ± 0.23 eV from ^{208}Pb, and 7.82 ± 0.14 eV from the combined carbon and lead analysis; the errors are statistical only.

<COMP: PLEASE INSERT TABLE 1 HERE>

The estimated total systematic error in $\Gamma(\pi^0 \to \gamma\gamma)$ is estimated to be ±0.17 eV (±2.1%). The two largest contributions to this systematic error are from (*a*) fitting the $M_{\gamma\gamma}$ and elasticity distributions (±1.6%) and (*b*) knowledge of the photon flux (±1.1%). The theoretical model used for fitting the nuclear-incoherent background is the Glauber model (55). The multicollision intranuclear cascade model (36) was also used to check the model dependency of the extracted decay width. The estimated uncertainty in $\Gamma(\pi^0 \to \gamma\gamma)$ due to model dependency in $d\sigma_{NI}/d\Omega$ is ±0.3%.

That the fitted parameters C_{NC} and C_{NI} differ from unity indicates that the theoretical models used for the nuclear-coherent and -incoherent cross sections are limited in their ability to predict these processes. Nevertheless, one might expect that the systematic error introduced into the measurement of $\Gamma(\pi^0 \to \gamma\gamma)$ from model errors in $d\sigma_{NC}/d\Omega$ and $d\sigma_{NI}/d\Omega$ is small because the nuclear-coherent and -incoherent cross sections are relatively small in the Primakoff peak region.

The radiative width from the combined carbon and lead analysis, $\Gamma(\pi^0 \to \gamma\gamma) =$ 7.82 ± 0.14 (stat.) ± 0.17 (sys.) eV, is shown in **Figure 4** with the errors combined in quadrature. The result is in agreement with the chiral anomaly, the NLO ChPT calculations, and the QCD sum rule prediction.

7. PRIMAKOFF EXPERIMENTS AT 12 GeV AT THE JEFFERSON LABORATORY

In the near future, the electron-beam energy at JLab will be upgraded to 12 GeV (12-GeV JLab). A natural extension of the π^0 experiment, and one that will be well suited to 12-GeV JLab, will be to measure the $\eta \to \gamma\gamma$ radiative width. Furthermore, no Primakoff measurements exist for the $\eta' \to \gamma\gamma$ width.

The η decay width is given by $\Gamma(\eta \to \gamma\gamma) = (m_\eta^3/4\pi)|\kappa_\eta|^2$ with a similar expression for $\Gamma(\eta' \to \gamma\gamma)$. At NLO in the chiral and $1/N_C$ expansions, the matrix elements κ_η and $\kappa_{\eta'}$ depend on two unknowns: the mixing angle θ between the pure $SU(3)$ states η_8 and η_0 and the NLO correction to the F_{00} decay matrix element (28, 56). Measurements of $\Gamma(\eta \to \gamma\gamma)$ and $\Gamma(\eta' \to \gamma\gamma)$ will allow the mixing angle θ and the correction to F_{00} to be determined. The effect of $\eta\pi^0$ mixing is relatively small, which leads to a reduction in $\Gamma(\pi^0 \to \gamma\gamma)$ of less than 1.5% (28).

The experimental situation for $\Gamma(\eta\to\gamma\gamma)$ is marked by the long-standing disagreement between the Primakoff result of Browman et al. (57) and the results from collider $e^+e^- \to e^+e^-\eta$ experiments (2). Recently, Rodrigues et al. (58) reanalyzed the Cornell Primakoff data by using the MCMC model to calculate the incoherent background. These authors obtained $\Gamma(\eta\to\gamma\gamma) = 0.476 \pm 0.062$ keV; this result is 50% higher than that of Browman et al. and agrees with the PDG average of 0.510 ± 0.026 keV (2). The analysis by Browman et al. assumed an isotropic angular distribution for the nuclear-incoherent scattering, which is incorrect at forward angles (36, 55). Although the discrepancy between the Primakoff and collider results has apparently been resolved, it is still important to reduce the uncertainty in $\Gamma(\eta\to\gamma\gamma)$ by use of the Primakoff reaction on the proton target, in which the nuclear-coherent scattering is well understood and the nuclear-incoherent process is absent.

The broader implication of a more precisely known measurement of $\Gamma(\eta\rightarrow\gamma\gamma)$ is that all other partial widths of the η will also be more precisely known, given that they are determined from $\Gamma(\eta\rightarrow\gamma\gamma)$ and the corresponding branching ratios. Of particular interest are the decay widths $\Gamma(\eta\rightarrow\pi^+\pi^-\pi^0)$ and $\Gamma(\eta\rightarrow\pi^0\pi^0\pi^0)$, as these reactions proceed primarily through isospin symmetry--breaking amplitudes that are proportional to m_d--m_u, thereby providing a sensitive determination of the quark mass ratio

$$Q^2 = \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2}, \quad 11.$$

where $\hat{m} = (m_u + m_d)/2$. The main error in determining Q by use of $\eta \rightarrow \pi\pi\pi$ decays is from the experimental uncertainty in the partial width $\Gamma(\eta\rightarrow\gamma\gamma)$ (59). The goal of experiment E1210011 at JLab is to measure $\Gamma(\eta\rightarrow\gamma\gamma)$ to a precision of ±3%. (56)

Q can also be determined through a ratio of meson masses:

$$Q^2 = \frac{M_K^2}{M_\pi^2}\frac{M_K^2 - M_\pi^2}{\left(M_{K^0}^2 - M_{K^+}^2\right)_{QCD}}\left[1 + O\left(m_{quark}^2\right)\right]. \quad 12.$$

However, the difficulty in using this ratio lies in removing the electromagnetic contribution to the K^0–K^+ mass difference. **Figure 11** shows both the sensitivity of Q to the K^+–K^0 electromagnetic mass correction, along with several calculations for that correction, and the value of Q from Cornell and the average of collider measurements of $\Gamma(\eta\rightarrow\gamma\gamma)$.

<COMP: PLEASE INSERT FIGURE 11 HERE>

Figure 11 (*Left*) The values of Q that correspond to the Primakoff and collider experimental results for $\Gamma(\eta\rightarrow\gamma\gamma)$. (*Right*) The results for Q obtained with four different theoretical estimates for the electromagnetic self-energies of kaons. Reproduced from Reference 59.

By going to higher incident energies, the proton becomes feasible as a Primakoff target because the peak cross section goes as E_γ^4. Laget (60) has calculated the Primakoff effect on a proton target for π^0 and η production by utilizing the latest developments in Regge theory to describe the nuclear-coherent amplitude. The coupling constants in the Regge amplitude are constrained by π^0 and η photoproduction at forward angles; the only free parameter in the calculation is the relative sign between the Primakoff and strong amplitudes. **Figure 12** shows the predicted differential cross sections at $E_\gamma = 5.80$ GeV as a function of t, the four-momentum transfer to the proton. The data points are from the π^0 Primakoff experiment on a proton target at DESY (37). Sibirtsev et al. (61) have extended the Regge analysis of the η photoproduction amplitude to include beam and target-polarization observables. The next generation of Primakoff experiments at 12-GeV JLab will use the proton as a target (56).

<COMP: PLEASE INSERT FIGURE 12 HERE>

Figure 12 Angular distribution of π^0 mesons in $\gamma p \rightarrow \pi^0 p$ at $E_\gamma = 5.8$ GeV. The dashed curve represents the nuclear-coherent cross section, and the solid curve represents the sum of Primakoff and nuclear-coherent amplitudes. The sign of the Primakoff amplitude is changed in the dotted curve. Reproduced from Reference 60. The data are from Reference 37.

8. SUMMARY AND OUTLOOK

The final PrimEx result from the combined carbon and lead analysis is $\Gamma(\pi^0 \rightarrow \gamma\gamma) = 7.82 \pm 0.14$ (stat.) ± 0.17 (sys.) eV. This result is in agreement with both the chiral anomaly prediction and the NLO ChPT calculations. The total error is 2.8%, an uncertainty approximately 2.1 times smaller than the current average quoted by PDG.

The extension of the PrimEx experiment recently took data at JLab. The targets in this experiment were carbon and silicon (10% radiation length each); other aspects of the experiment were nearly identical to the conditions of PrimEx. In the second phase of this experiment, the uncertainty in $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ is expected to be reduced to 1.4% through the combination of new data with existing data.

Reducing the total error in $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ below ~1% in a future Primakoff experiment will be difficult because the dominant errors become systematic, as opposed to statistical. Chief among the systematic errors is the photon-flux measurement. By making a simultaneous relative measurement to a known QED process, such as atomic Compton scattering, one can eliminate the flux systematic error. Through the use of the electron as a Primakoff target, the nuclear backgrounds, both coherent and incoherent, can be eliminated. The minimum photon-beam energy required to do so, however, is approximately 20 GeV.

The experimental prospects for a Primakoff program at 12-GeV JLab are very rich: The increased beam energy will allow access to $\Gamma(\eta \rightarrow \gamma\gamma)$ and, therefore, the η_0–η_0' mixing angle and the quark mass ratio Q. Because of the larger mass of η' relative to π^0 or η, measuring the η' radiative width at 12-GeV JLab will be difficult. If we define a figure of merit as $Z^2 E_\gamma^4/m^3$, the figure of merit for a 12-GeV η' experiment on a proton will be reduced by a factor of approximately 0.001, compared with the PrimEx π^0 result with a ^{12}C target. Notably, at the proposed electron-ion collider (http://www.bnl.gov/cad/eRhic/), whose electron- and proton-beam energies will be as high as 30 GeV and 325 GeV, respectively, the incident photon energy in the proton rest frame may be as high as 21 TeV.

DISCLOSURE STATEMENT

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Table 1 Results from fitting differential cross sections

Target	**$\Gamma(\pi^0 \to \gamma\gamma)$[a] (eV)**	**C_{NC}[b]**	**φ (radians)**	**C_{NI}**
^{12}C	7.79±0.18	0.83±0.02	0.78±0.07	0.72±0.06
^{208}Pb	7.85±0.23	0.69±0.04	1.25±0.07	0.68±0.12
Combined fit[c]	7.82±0.14±0.17	---	---	---

[a]The values for $\Gamma(\pi^0 \to \gamma\gamma)$ are the weighted averages of Analyses I and II.

[b]The parameters C_{NC}, φ, and C_{NI} are from Analysis II; the results from Analysis I are similar.

[c]The errors in the combined fit are statistical and systematic, respectively.