Precision Measurement of the Neutral Pion Lifetime

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The explicit breaking of the axial symmetry by quantum fluctuations gives rise to the so-called axial anomaly. This phenomenon is solely responsible for the decay of the neutral pion π^0 into two photons, leading to its unusually short lifetime. We measured the decay width Γ of the $\pi^0 \to \gamma\gamma$ process with unprecedented precision. The differential cross sections for π^0 photoproduction at forward angles were measured on two targets: ^{12}C and ^{28}Si, yielding $\Gamma(\pi^0 \to \gamma\gamma) = 7.798 \pm 0.056$ (stat.) ± 0.109 (syst.) eV. Combining the results of this and an earlier experiment led to a weighted average of $\Gamma(\pi^0 \to \gamma\gamma) = 7.802 \pm 0.052$ (stat.) ± 0.105 (syst.) eV. Our final result has a total uncertainty of 1.50% and confirms the prediction based on the chiral anomaly in quantum chromodynamics.

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The basic symmetries of the classical world are at the origin of the most fundamental conservation laws. Classical symmetries are generally respected in the quantum realm, but it was realized several decades ago that there are exceptions to this rule in the form of so-called "anomalies". The most famous one is arguably the axial anomaly, which enables a process of decay of a light hadron called the neutral π meson into two photons, denoted as $\pi^0 \to \gamma\gamma$. π mesons were first proposed by Yukawa [1] as the intermediaries of nuclear interactions; they result from a profound phenomenon central to strong interaction physics described by Quantum Chromodynamics (QCD), the theory of quarks and gluons. These three pions (π^+, π^- and π^0) consist of light quark-antiquark pairs coupled together by exchange of gluons. The axial anomaly is represented by truly unique graphs in perturbative quantum field theory that do not require renormalization, thereby enabling a purely analytical prediction from QCD – the π^0 lifetime. Generally, QCD can analytically predict only relative features and needs either experimental data, models or numerical inputs on the lattice, to anchor these relative predictions. Thus, experimental verification of this phenomenon with highest accuracy is a unique test of quantum field theory

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and of symmetry breaking by pure quantum effects [2].

The fact that the three light quarks, u, d and s, have much smaller masses than the energy scale of QCD gives rise to an approximate chiral flavor symmetry consisting of chiral left-right and axial symmetries. The chiral symmetry is spontaneously broken by the non-perturbative dynamics of QCD which leads to the condensation of quark pairs, the $\langle \bar{q}q \rangle$ condensate. This phenomenon is responsible for the observed octet of light pseudoscalar mesons in nature, with π^0 being one of them. The axial symmetry is explicitly broken by the quantum phenomenon known as the axial (or chiral) anomaly [3], originating from the quantum fluctuations of the quark and gluon fields. The chiral anomaly drives the decay of the π^0 into two photons with the predicted decay width [4]:

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

where α is the fine-structure constant, m_{π^0} is the π^0 mass, $N_c = 3$ is the number of colors in QCD, and F_{π^0} is the pion decay constant; $F_{\pi^0} = 92.277 \pm 0.095\,\text{MeV}$ extracted from the charged pion weak decay [5]; note that there are no free parameters.

The study of corrections to the chiral anomaly prediction has been mainly done with Chiral Perturbation Theory (ChPT), with the three light flavors. The dominant corrections are the result of meson state mixing caused by the differences between the quark masses. The π^0 mixes with the η and η' meson owing to the isospin symmetry breaking, which is in turn a consequence of $m_u < m_d$; the correction is calculable in a global analysis of the three neutral mesons [6]. In ref. [6] the $\Gamma(\pi^0 \to \gamma\gamma)$ width was calculated in a combined framework of ChPT and $1/N_C$ expansion up to $\mathcal{O}(p^6)$ and $\mathcal{O}(p^4 \times 1/N_C)$ in the decay amplitude (GBH, NLO). Their result, $\Gamma(\pi^0 \to \gamma\gamma) = 8.10 \pm 0.08\,\text{eV}$ with $\sim$1% estimated uncertainty is about 4.5% higher than the prediction of chiral anomaly. Another Next-to-Leading-Order (NLO) calculation in ChPT was performed in [7], resulting in $8.06 \pm 0.06\,\text{eV}$ (AM, NLO). The only Next-to-Next-to-Leading-Order (NNLO) calculation for the decay width was performed in [8] yielding a similar result, $8.09 \pm 0.11\,\text{eV}$. The calculations of the corrections to the chiral anomaly in the framework of QCD using dispersion relations and sum rules in ref. [9] resulted in the value of $7.93 \pm 0.12\,\text{eV}$, which is about 2% lower than the ChPT predictions. The fact that these calculations performed by different methods differ from the chiral anomaly prediction by a few percent, with an accuracy of approximately one percent, makes the precision measurement of the $\pi^0 \to \gamma\gamma$ width a definitive low-energy test of QCD.

In past decades, there have been extensive efforts to measure the π^0 radiative decay width using three experimental methods: the Primakoff, the direct, and the collider methods. The current Particle Data Group (PDG) value of $\pi^0 \to \gamma\gamma$ decay width is $7.63 \pm 0.16\,\text{eV}$ [5]. It is the average of five measurements: two Primakoff type, Cornell University (Cornell, (Prim.)) [10] with $7.92 \pm 0.42\,\text{eV}$, and Jefferson Laboratory (JLab, PrimEx-I (Prim.)) [11] with $7.82 \pm 0.14\,(\text{stat.}) \pm 0.17\,(\text{syst.})\,\text{eV}$; a direct measurement, European Center for Nuclear Research (CERN (Dir.)) [12] with $7.25 \pm 0.18\,(\text{stat.}) \pm 0.14\,(\text{syst.})\,\text{eV}$; a collider measurement by Crystal Ball (CBAL (Col.)) at Deutsches Electronen-SYnchrotron (DESY) [13] with $7.7 \pm 0.72\,\text{eV}$; a measurement from radiative PIon BETA decay (PIBETA) [14] with $7.74 \pm 1.02\,\text{eV}$. The result from the PrimEx-I experiment [11] improved the uncertainty on the decay width quoted in the previous PDG [15] value by a factor of two-and-a-half and confirmed the validity of the chiral anomaly at the few percent level. However, there is a 6% discrepancy between the two most precise experiments included in the PDG average, the CERN direct [12] and PrimEx-I Primakoff [11]. Furthermore, the accuracy of the PDG average is still not adequate to test the theory corrections to the prediction of the anomaly. The PrimEx-II experiment was conducted at JLab to address these issues.

To reach a percent level precision in the extracted $\pi^0 \to \gamma\gamma$ decay width we have implemented several basic improvements in the experimental technique (schematically shown in Fig. 1) used in the previous Primakoff type of experiments. The existing tagged photon beam facility (Tagger [16]) in Hall B at JLab was used allowing critical improvements in the background separation and the determination of the photon flux. Instead of the traditionally used Pb-glass based electromagnetic calorimeter, used in the previous experiments, we developed and constructed a novel $PbWO_4$ crystal based multi-channel, high resolution and large acceptance electromagnetic calorimeter (HyCal) [17]. The combination of these two techniques greatly improved the angular resolution of the photoproduced π^0s, which is critical for Primakoff type measurements, and significantly reduced the systematic uncertainties that were present in previous experiments. In addition, the cross sections of two well-known electromagnetic processes, Compton scattering and e^+e^- pair production from the same experimental target, were periodically measured during the experiment to validate the extracted π^0 photoproduction cross sections and their estimated systematic uncertainties. Tagged photons with known energy and timing were incident on the production targets located in the entrance of the large acceptance dipole magnet (8% radiation length (r.l.) ^{12}C and 10% r.l. ^{28}Si solid targets were used). This magnet played two important roles in the experiment: deflect all charge particles produced in the target from the HyCal acceptance; and detection of e^+e^- pairs produced in the target (Pair Spectrometer, PS) allowing continuous measurement of the relative photon tagging efficiencies during the experiment. The decay photons from the photoproduced π^0s traveled through the Vacuum Chamber (VCh) and the Helium Bag (HB) and were detected in the HyCal calorimeter located 7 m downstream from the targets. Two-planes of scintillator counters (Veto Counters, VC), located in front of HyCal, provided rejection of charged particles and effectively reduced the background in the experiment. A more detailed description of the experimental setup is presented in the Supplementary Materials (section S2). In this experiment we measured the differential cross sections for the photoproduced π^0 mesons at forward angles on two targets. At these small angles the π^0s are produced by two different elementary mechanisms: by one photon exchange (the so-called Primakoff process); and by a hadron exchange (the so-called strong process). The amplitudes of these processes contribute both coherently and incoherently in the π^0 photoproduction cross sections at forward angles (see Eq. S1). The cross section of the Primakoff process is directly proportional to the $\pi^0 \to \gamma\gamma$ decay width, allowing its extraction from the measured differential cross sections with high accuracy. More detail description of these processes and our fitting procedure to extract the decay width is presented in Section S3.

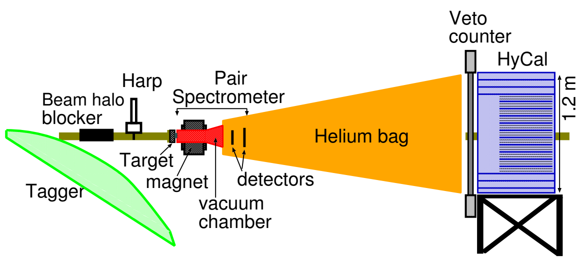

FIG. 1: Schematic view of the PrimEx-II experimental setup (not to scale, see the text for description of individual detectors and components).

PrimEx-I achieved a total uncertainty of 2.8% in the extracted width $\Gamma(\pi^0 \to \gamma\gamma)$ [11]. The PrimEx-II experiment aimed to significantly increase the statistics and improve the systematic uncertainties to reach the percent level accuracy. The following was implemented to increase the statistics by a factor of six: (i) the accepted energy interval of the tagged photons was increased by 50%; (ii) thicker solid targets were used: 8% radiation length (r.l.) ^{12}C and 10% r.l. ^{28}Si; (iii) the performance of the data acquisition (both at electronics and software levels) was upgraded to increase the data taking rate by a factor of five. The systematic uncertainties were also reduced thanks to several improvements: (i) the central part of the HyCal (about 400 modules) was equipped with individual Time-to-Digital Converters (TDC) for better rejection of time accidental events; (ii) the trigger for the experiment was simplified by using only events with a total deposited energy above 2.5 GeV in HyCal; (iii) a new set of 12 horizontal scintillator veto counters was added for better rejection of charged particles in HyCal (see Fig. 1); (iv) the distance between the calorimeter and target was reduced to 7 m, which allowed for better geometrical acceptance between 1.0° to 2.0° in the π^0 production angles, and improved separation of the nuclear coherent and incoherent production terms from the Primakoff process in the measured cross sections (see Eq. S1). In addition, the improved running conditions (beam intensity and position stability, etc.) of the JLab accelerator allowed for a significant reduction of the beam-related systematic uncertainties. Using an intermediate-atomic-number target, ^{28}Si, in combination with a low-atomic-number target, ^{12}C, allowed more effective control of systematic uncertainties related to the extraction of the Primakoff contribution. Similar to the PrimEx-I experiment [11], the combination of the photon tagger with its well-defined photon energy and timing together with the HyCal calorimeter defined the event selection criteria.

The event yield (the number of elastically produced π^0 events for each angular bin) was extracted using the kinematic constraints and by fitting the experimental two-photon invariant mass spectra ($M_{\gamma\gamma}$) to subtract the background contributions. Two independent analysis methods, the "constrained" and "hybrid" mass methods were used to extract the event yield in this experiment. The two methods (integrated over the angular range of $\theta_\pi = 0°$–$2.5°$ and for the incident energies $E_\gamma = 4.45 - 5.30$ GeV) agree with each other. The total integrated statistics was about 83,000 π^0 events on ^{12}C and 166,000 on ^{28}Si targets, a factor of six increase compared to PrimEx-I. This reduced the statistically limited part of the systematic uncertainties in the yield extraction process. Combining the two analysis methods with the partially independent systematics further reduced the systematic uncertainty to 0.80%. This includes the uncertainty in the physics background subtraction, 0.10%, mostly from ω mesons photoproduction. High precision monitoring of the photon beam flux during the entire data taking process is one of the challenging tasks for this type of experiment [18]. The photon tagger was used for measurements of the photon beam flux, a Total Absorption Counter (TAC) for periodic measurements of the absolute tagging ratios, and a pair-spectrometer (PS) for continuous monitoring of the relative tagging ratios and tagger stability [18]. The stability of the beam parameters (position, width, and frequency of interruptions) was far better than during PrimEx-I. That, and more frequent TAC measurements, led to a better measurement of the photon flux (0.80% relative uncertainty was reached in this experiment). Different measurement methods allowed to achieve a sub-percent accuracy for the uncertainty in the number of target nuclei per cm^2: less than 0.10% for ^{12}C and 0.35% for ^{28}Si targets [19, 20]. The geometrical acceptances and resolutions of the experimental setup have been calculated by a standard nuclear physics Monte Carlo simulation package. The contributed uncertainty in the extracted cross sections from this part is estimated to be 0.55%.

The extracted differential cross sections of π^0 photoproduction on both ^{12}C and ^{28}Si are shown in Fig. 2. They are integrated over the incident photon beam energies of 4.45 to 5.30 GeV (with the weighted average value of 4.90 GeV). The fit results for the four processes contributing to forward production: Primakoff, nuclear coherent, interference between them, and nuclear incoherent are also shown.

The $\pi^0 \to \gamma\gamma$ decay width was extracted by fitting the experimental differential cross sections to the theoretical terms of four contributing processes (see Eq. S1), convoluted with the angular resolution, experimental acceptances and folded with the measured incident photon energy spectrum. The effect of final state interactions between the outgoing pion and the nuclear target, and the photon shadowing effect in nuclear matter must be accurately included in the theoretical cross sections for the precise extraction of the Primakoff term, and therefore, $\Gamma(\pi^0 \to \gamma\gamma)$ [21, 22]. Within our collaboration, two separate groups analyzed the data using different methods. They extracted $\Gamma(\pi^0 \to \gamma\gamma)$ from their cross sections using similar fitting procedures (shown in Table S1). Thus, for the same target, the statistical and part of the systematic uncertainties from the two analysis groups are correlated. This was accounted for when the two results were combined [23]. Results for the individual targets were obtained by using the weighted average method, yielding: $\Gamma(\pi^0 \to \gamma\gamma) = 7.763 \pm 0.127\,(\text{stat.}) \pm 0.117\,(\text{syst.})$ eV for ^{12}C, and $7.806 \pm 0.062\,(\text{stat.}) \pm 0.109\,(\text{syst.})$ eV for ^{28}Si. The results from the two different targets were then combined to give the final result: $\Gamma(\pi^0 \to \gamma\gamma) = 7.798 \pm 0.056\,(\text{stat.}) \pm 0.109\,(\text{syst.})$ eV, with a total uncertainty of 1.57% (see Fig. 3).

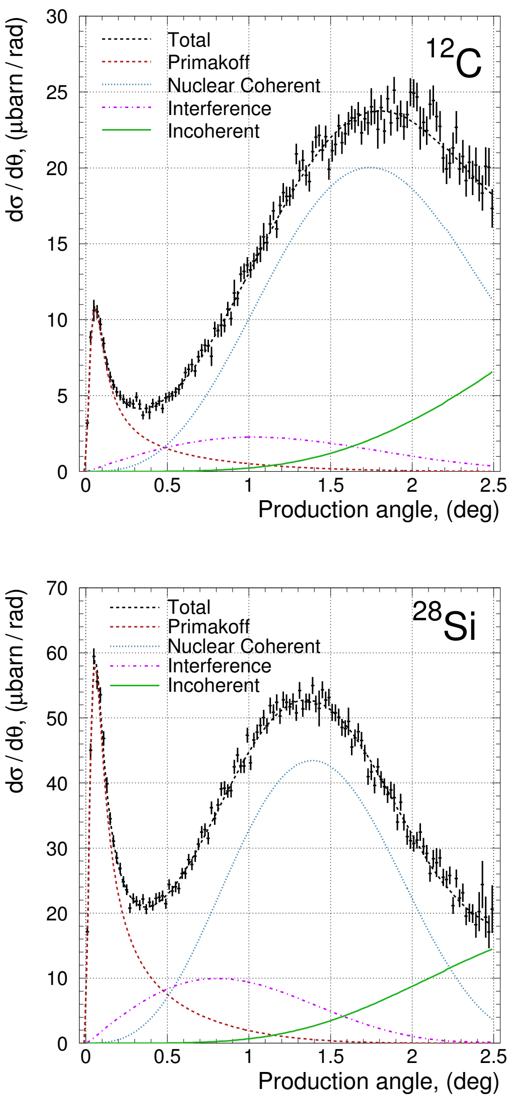

FIG. 2: Experimental differential cross section as a function of the π^0 production angle for ^{12}C (top) and ^{28}Si (bottom) together with the fit results for the different physics processes (see insert and text for explanations).

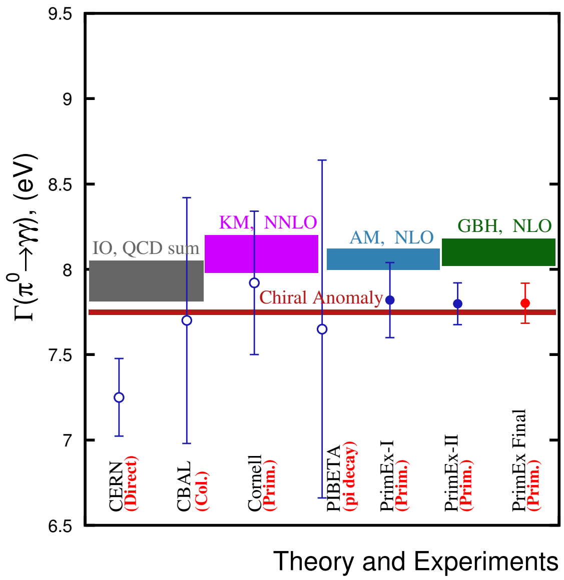

FIG. 3: Theoretical predictions and experimental results of the $\pi^0 \to \gamma\gamma$ decay width. Theory: chiral anomaly [3] (dark red band); IO, QCD sum rule [9] (gray band); KM, ChPT NNLO [8] (magenta band); AM, ChPT NLO [7] (blue band); GBH, ChPT NLO [6] (green band). Experiments included in the current PDG [5]: CERN direct [12]; Crystal Ball collider [13]; Cornell Primakoff [10]; PIBETA [14]; PrimEx-I [11]. Our new results: PrimEx-II and the PrimEx combined.

To check the sensitivity of the extracted decay width to the theory parameters (nuclear matter density, nuclear radii, photon shadowing parameter, $\pi^0 N$ total cross section, etc.), the values of these parameters were changed by several sigmas and the cross sections were refitted to obtain new decay widths. Using this procedure, the two main contributors to the systematic uncertainties were found to be the nuclear radii and the photon shadowing parameter ([24], [25]). The nuclear coherent process, which dominates at larger angles for both targets, was determined with a high precision (see Fig. 2), and this information was used to extract the nuclear radii for the targets. To do so, the radii were varied around the experimental values obtained from electron scattering data [26, 27], known to better than 0.6%. Then, the best values for the nuclear radii were defined by minimizing the resulting χ^2 distributions. Our extracted results for the nuclear radii are: 2.457 ± 0.047 fm for ^{12}C and 3.073 ± 0.018 fm for ^{28}Si. They agree with the radii extracted from electron scattering [26, 27]. The shadowing parameter was extracted by a similar procedure. The extracted value is: $\xi = 0.30 \pm 0.17$, agreeing with two previous measurements: 0.25-0.50 from [24] and 0.31 ± 0.12 from [25]. Varying this parameter within a $3\,\sigma$ interval gave only a 0.30% uncertainty in the extracted $\Gamma(\pi^0 \to \gamma\gamma)$ (correlated between the two targets). Our systematic uncertainties are described in greater detail in Section S3 and are summarized in Tables S2 and S3.

For both PrimEx-I and PrimEx-II, the experimental uncertainties have been validated by periodically measuring the Compton cross sections for the same nuclear targets. Our measured Compton cross sections agree with the theoretical simulations of this well-known Quantum Electrodynamics (QED) process to better than 1.7% [28].

If the results from the two PrimEx experiments are combined, correlations between different systematic uncertainties can be accounted for [23]. The weighted average final result for the $\pi^0 \to \gamma\gamma$ decay width from the two PrimEx experiments is $7.802 \pm 0.052\,(\text{stat.}) \pm 0.105\,(\text{syst.})\,\text{eV}$ (shown in Fig. 3), defining the new lifetime: $\tau = 8.337 \pm 0.056$ (stat.) ± 0.112 (syst.) $\times 10^{-17}$ s. With 1.50% total uncertainty, this is the most precise measurement of the $\Gamma(\pi^0 \to \gamma\gamma)$, and firmly confirms the prediction of the chiral anomaly in QCD at the percent level. As seen from Fig. 3, our result deviates from the theoretical corrections to the anomaly by two standard deviations.

The axial anomaly, which has historically provided strong evidence in favor of the color-charge concept in QCD, continues to teach us about the most fundamental aspects of nature, for example, by strictly constraining physics beyond the Standard Model (SM) and presenting a unique opportunity for measuring the light quark mass ratio. The $\Gamma(\pi^0 \to \gamma\gamma)$ decay width is a critical input for the normalization of the π^0 transition form factor to constrain the hadronic light-by-light scattering contributions to the well-known muon (g-2) anomaly in search of new physics [29]. The light quark masses are as yet unmeasured, and whether the masses are in fact observable is still under debate. Future directions include measuring the anomaly driven $\eta \to \gamma\gamma$ decay, which provides a unique normalization to the isospin-violating $\eta \to 3\pi$ decay that leads to a model independent extraction of the light quark mass ratio [30].

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Author contributions

A.G. is the spokesperson and contact person of the experiment. A.G.,R.M., D.D., L.G., M.M.I., M.K. and I.L. are the spokespersons of the experiment. A.G. developed the initial concepts of the experiment. A.G.,R.M., D.D., L.G., M.M.I., M.K. and I.L. designed, upgraded and proposed the experiment. The entire PrimEx collaboration constructed the experiment and worked on the data collection. The data acquisition code was developed and built by D.L.. The Monte Carlo simulation code was built and validated by I.L., P.A. and M.M.I. with input from other members of the collaboration. Calibrations were carried out by I.L., P.A., Y.Z., J.F., L.M., V.V.T. and L.Y.. Analysis software tools were developed by I.L., D.L., M.M.I., Y.Z., J.F., L.M. and V.V.T. with input from all spokespersons. The data analysis was carried out by I.L., Y.Z. with input from A.G.,R.M., D.D., L.G., M.M.I., H.G., D.D., D.S. and many authors of this article. All authors reviewed the manuscript.

Competing interests: The authors declare that they have no competing financial interests.

Data and materials availability: The raw data from this experiment together with all computer codes used for data analysis and simulation are archived in Jefferson Laboratory's mass storage silo.

Figure Captions:

Fig 1: **Experimental setup.** Schematic view of the PrimEx-II experimental setup (not to scale, see the text for description of individual detectors and components).

Fig 2: **Experimental cross sections.** Experimental differential cross section as a function of the π^0 production angle for ^{12}C (top) and ^{28}Si (bottom) together with the fit results for the different physics processes (see insert and text for explanations).

Fig 3: **Theoretical predictions and experimental results of the $\pi^0 \to \gamma\gamma$ decay width.** Theory: chiral anomaly [3] (dark red band); IO, QCD sum rule [9] (gray band); KM, ChPT NNLO [8] (magenta band); AM, ChPT NLO [7] (blue band); GBH, ChPT NLO [6] (green band). Experiments included in the current PDG [5]: CERN direct [12]; Crystal Ball collider [13]; Cornell Primakoff [10]; PIBETA [14]; PrimEx-I [11]. Our new results: PrimEx-II and the PrimEx combined (see the text for acronyms).