REPORT

NUCLEAR PHYSICS

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 ($\gamma\gamma$), leading to its unusually short lifetime. We precisely measured the decay width Γ of the $\pi^0 \rightarrow \gamma\gamma$ process. The differential cross sections for π^0 photoproduction at forward angles were measured on two targets, carbon-12 and silicon-28, yielding $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ = 7.798 ± 0.056(stat.) ± 0.109(syst.) eV, where stat. denotes the statistical uncertainty and syst. the systematic uncertainty. We combined the results of this and an earlier experiment to generate a weighted average of $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ = 7.802 ± 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.

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 $\pi^0 \rightarrow \gamma\gamma$. π mesons were first proposed by Yukawa (*1*) as the intermediaries of nuclear interactions; they result from a 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 by the exchange of gluons. The axial anomaly is represented by 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 requires experimental data, models, or numerical inputs on the lattice to anchor these relative predictions. Thus, experimental verification of this phenomenon with the highest accuracy is a test of quantum field theory 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 nonperturbative 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 the π^0 being one of them. The axial symmetry is explicitly broken by the axial (or chiral) anomaly (*3*, *4*), 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 (*5*)

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

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. $F_{\pi^0} = 92.277 \pm 0.095$ MeV extracted from the charged pion weak decay (*6*); 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′ mesons, 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 (*7*). The $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ 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 (Goity-Bernstein-Holstein), next-to-leading order (NLO); $\mathcal{O}$, low-energy expansion order; p, any low-energy quantity, such as momentum] (*7*). Their result, $\Gamma(\pi^0 \rightarrow \gamma\gamma) = 8.10 \pm 0.08$ eV with ~1% estimated uncertainty, is ~4.5% higher than the prediction of chiral anomaly. Another NLO calculation in ChPT was performed, resulting in 8.06 ± 0.06 eV [AM (Ananthanarayan-Moussallam), NLO] (*8*). The only next-to-next-to-leading-order (NNLO) calculation for the decay width was subsequently performed (*9*), yielding a similar result: 8.09 ± 0.11 eV. The calculations of the corrections to the chiral anomaly in the framework of QCD using dispersion relations and sum rules in (*10*) resulted in the value of 7.93 ± 0.12 eV, which is ~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 ~1%, makes the precision measurement of the $\pi^0 \rightarrow \gamma\gamma$ width a definitive low-energy test of QCD.

In past decades, there have been extensive efforts to measure the π^0 radiative decay width by three experimental methods: the Primakoff, direct, and collider methods. The current

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particle data group (PDG) value of the $\pi^0 \rightarrow \gamma\gamma$ decay width is 7.63 ± 0.16 eV (*6*). This value is the average of five measurements: two Primakoff-type measurements, one from Cornell University [Cornell (Prim.), 7.92 ± 0.42 eV (*11*)] and another from the Jefferson Laboratory [JLab, PrimEx-I (Prim.), 7.82 ± 0.14(stat.) ± 0.17(syst.) eV (stat., statistical uncertainty; syst., systematic uncertainty) (*12*)]; a direct measurement from the European Center for Nuclear Research [CERN (Dir.), 7.25 ± 0.18(stat.) ± 0.14(syst.) eV (*13*)]; a collider measurement from the Crystal Ball detector at Deutsches Electronen-Synchrotron [CBAL (Col.), 7.7 ± 0.72 eV (*14*)]; and a measurement from radiative pion beta decay [(PIBETA), 7.74 ± 1.02 eV (*15*)]. The result from the PrimEx-I experiment (*12*) improved the uncertainty on the decay width quoted in the previous PDG (*16*) value by a factor of 2.5 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 (*13*) and PrimEx-I Primakoff (*12*) values. 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 1.5% precision in the extracted $\pi^0 \rightarrow \gamma\gamma$ decay width, we implemented several basic improvements in the experimental technique (schematically shown in Fig. 1) used in the previous Primakoff-type experiments. The existing tagged photon beam facility [Tagger (*17*)] in Hall B at JLab was used, thus allowing critical improvements in the background separation and the determination of the photon flux. Instead of the traditional Pb-glass–based electromagnetic calorimeter from the previous experiments, we developed and constructed a $PbWO_4$ crystal–based multichannel, high-resolution, and large-acceptance electromagnetic calorimeter (HyCal) (*18*). The combination of these two techniques greatly improved the angular resolution of the photoproduced π^0s, which is critical for Primakoff-type measurements, and substantially reduced the systematic uncertainties that were present in previous experiments. In addition, the cross sections of two well-known electromagnetic processes—Compton scattering and positron-electron (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 had two key roles in the experiment: deflecting all charged particles produced in the target from the HyCal acceptance and detecting 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 and the helium bag and were detected in the HyCal calorimeter located 7 m downstream from the targets. Two-planes of scintillator counters (veto counters), 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 section 2 of (*19*).

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: one-photon exchange (the so-called Primakoff process) and 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 (eq. S1). The cross section of the Primakoff process is directly proportional to the $\pi^0 \rightarrow \gamma\gamma$ decay width, allowing its extraction from the measured differential cross sections with high accuracy. A more detailed description of these processes and our fitting procedure to extract the decay width is presented in section 3 of (*19*).

PrimEx-I achieved a total uncertainty of 2.8% in the extracted width $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ (*12*). The PrimEx-II experiment aimed to significantly increase the statistics and improve the systematic uncertainties to reach percent-level accuracy. The following modifications were implemented to increase the statistics by a factor of 6: (i) the accepted energy interval of the tagged photons was increased by 50%; (ii) thicker solid targets were used (8% r.l. ^{12}C and 10% r.l. ^{28}Si; and (iii) data acquisition performance (at both electronics and software levels) was upgraded to increase the data-taking rate by a factor of 5. The systematic uncertainties were also reduced, owing to several improvements: (i) the central part of the HyCal (~400 modules) was equipped with individual time-to-digital converters 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 (Fig. 1); and (iv) the distance between calorimeter and target was reduced to 7 m, which allowed for better geometrical acceptance between 1.0° and 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 (eq. S1). In addition, the improved running conditions (e.g., beam intensity and position stability) of the JLab accelerator allowed for a substantial 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 (*12*), the combination of the photon tagger, with its well-defined photon energy and timing, and 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 by using the kinematic constraints and 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 θ_π = 0° to 2.5° and for the incident energies $E\gamma$ = 4.45 to 5.30 GeV) are in agreement. The total integrated statistics was ~83,000 π^0 events on ^{12}C targets

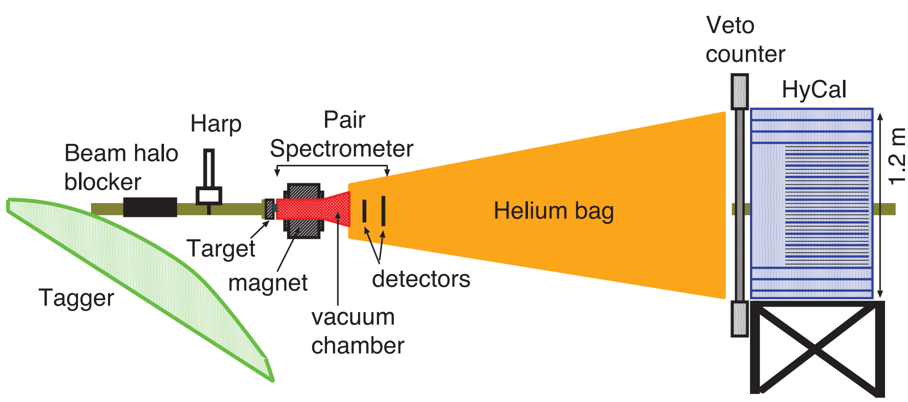

Fig. 1. Experimental setup. Schematic view of the PrimEx-II experimental setup (not to scale; see the text for a description of individual detectors and components).

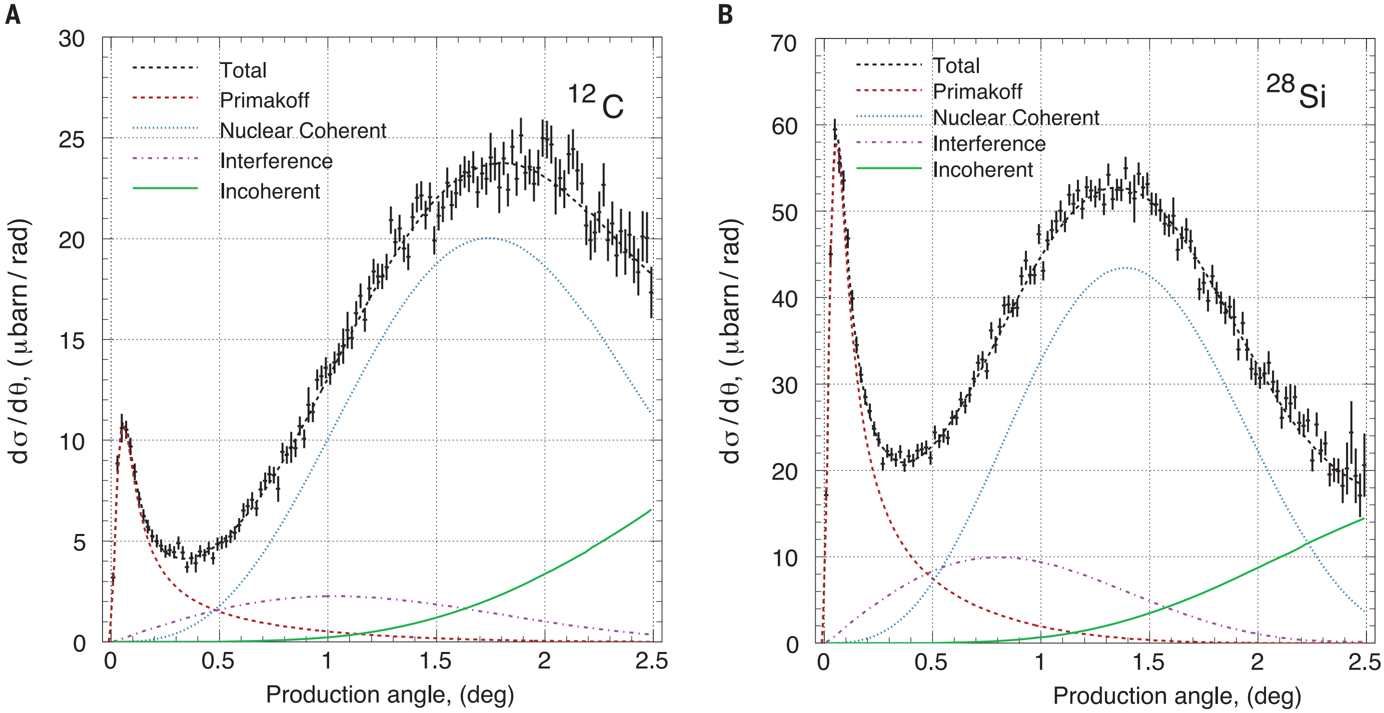

Fig. 2. Experimental cross sections. Experimental differential cross section as a function of the π^0 production angle for ^{12}C (**A**) and ^{28}Si (**B**) together with the fit results for the different physics processes (see text for explanations). Error bars indicate only statistical uncertainties.

and 166,000 events on ^{28}Si targets, a factor-of-6 increase compared with the PrimEx-I values. This result 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 meson photoproduction.

High-precision monitoring of the photon beam flux during the entire data-taking process is one of the challenging aspects of this type of experiment (*20*). 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 PS for continuous monitoring of the relative tagging ratios and tagger stability (*20*). The stability of the beam parameters (position, width, and frequency of interruptions) was far better than during the PrimEx-I experiment. This, along with more frequent TAC measurements, led to a more accurate measurement of the photon flux (0.80% relative uncertainty was reached in this experiment). Different measurement methods allowed us to achieve subpercent accuracy for the uncertainty in the number of target nuclei per square centimeter: less than 0.10% for ^{12}C targets and 0.35% for ^{28}Si targets (*21*, *22*). 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 (weighted average of 4.90 GeV). The fit results for the four processes that contribute to forward production—Primakoff process, nuclear coherent process, interference between the Primakoff and nuclear coherent amplitudes, and nuclear incoherent process—are also shown.

The $\pi^0 \rightarrow \gamma\gamma$ decay width was extracted by fitting the experimental differential cross sections to the theoretical terms of four contributing processes (eq. S1), convoluted with the angular resolution and 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, $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ (*23*, *24*). Within our collaboration, two separate groups used different methods to analyze the data. They extracted $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ from their cross sections by using similar fitting procedures (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 (*25*). Results for the individual targets were obtained through the weighted average method, yielding: $\Gamma(\pi^0 \rightarrow \gamma\gamma) = 7.763 \pm 0.127(\text{stat.}) \pm 0.117(\text{syst.})$ 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 generate the final result: $\Gamma(\pi^0 \rightarrow \gamma\gamma) = 7.798 \pm 0.056(\text{stat.}) \pm 0.109(\text{syst.})$ eV, with a total uncertainty of 1.57% (Fig. 3).

To check the sensitivity of the extracted decay width to the theory parameters (e.g., nuclear matter density, nuclear radii, photon shadowing parameter, $\pi^0 N$ total cross section), the values of these parameters were changed by several standard deviations and the cross sections were refitted to obtain new decay widths. Using this procedure, we found that the two main contributors to the systematic uncertainties were the nuclear radii and the photon shadowing parameter (*26*, *27*). The nuclear coherent process, which dominates at larger angles for both targets, was determined with high precision (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 (*28*, *29*), known to better than 0.6% uncertainty. 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

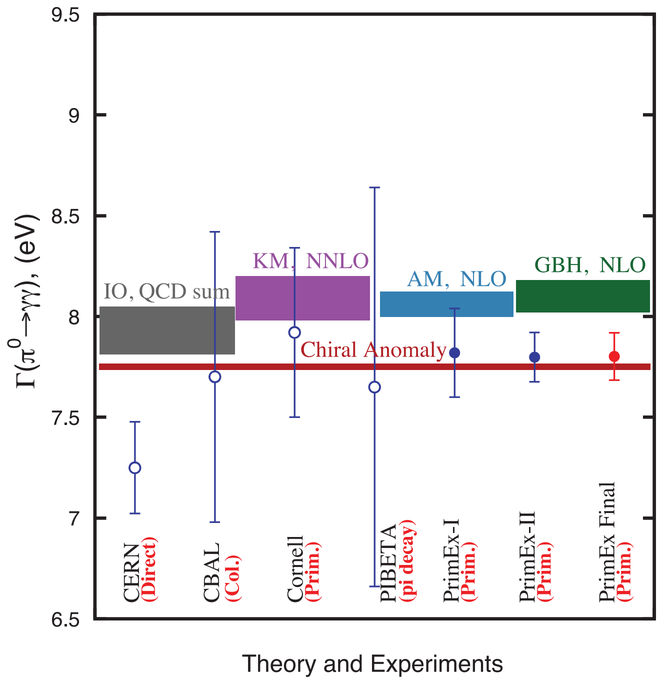

Fig. 3. Theoretical predictions and experimental results of the $\pi^0 \rightarrow \gamma\gamma$ decay width. Theory: chiral anomaly (*3*) (red band); IO (Ioffe-Oganesian), QCD sum rule (*10*) (gray band); KM (Kampf-Moussallam), ChPT NNLO (*9*) (purple band); AM, ChPT NLO (*8*) (blue band); and GBH, ChPT NLO (*7*) (green band). Experiments included in the current PDG (*6*): CERN direct (*13*), Crystal Ball (CBAL) collider (*14*), Cornell Primakoff (*11*), PIBETA (*15*), and PrimEx-I (*12*). Our results: PrimEx-II and the PrimEx combined (PrimEx Final). Open circles, experiments before PrimEx; filled circles, PrimEx experiments. Error bars indicate total experimental uncertainties.

for ^{28}Si. These values are consistent with the radii extracted from electron scattering (*28*, *29*). The shadowing parameter was extracted by a similar procedure. The extracted value is ξ = 0.30 ± 0.17, consistent with two previous measurements: [0.25 to 0.50 (*26*) and 0.31 ± 0.12 (*27*)]. Varying this parameter within a 3σ interval generated only a 0.30% uncertainty in the extracted $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ (correlated between the two targets). Our systematic uncertainties are described in greater detail in section 3 of (*19*) and are summarized in tables S2 and S3.

For both PrimEx-I and PrimEx-II experiments, 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 process to better than 1.7% uncertainty (*30*).

If the results from the two PrimEx experiments are combined, correlations between different systematic uncertainties can be accounted for (*25*). The weighted average final result for the $\pi^0 \rightarrow \gamma\gamma$ decay width from the two PrimEx experiments is $7.806 \pm 0.052(\text{stat.}) \pm 0.105(\text{syst.})\text{eV}$ (Fig. 3), defining the new lifetime: $\tau = 8.337 \pm 0.056(\text{stat.}) \pm 0.112(\text{syst.}) \times 10^{-17}$ s. With 1.50% total uncertainty, this is the most precise measurement of the $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ decay width and 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 and presenting an opportunity for measuring the light quark mass ratio. The $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ 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, toward the pursuit of new physics (*31*). The light quark masses are as yet unmeasured, and whether the masses are truly observable is still a matter of debate. Future directions include measuring the anomaly-driven $\eta \rightarrow \gamma\gamma$ decay, which provides a normalization to the isospin-violating $\eta \rightarrow 3\pi$ decay that leads to a model-independent extraction of the light quark mass ratio (*32*).

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SUPPLEMENTARY MATERIALS

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Supplementary Text
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References (*34*–*36*)

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Precision measurement of the neutral pion lifetime

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Testing the chiral anomaly

Pi mesons, also known as pions, consist of a quark and an antiquark and are extremely unstable. Neutral pions have a lifetime of only ~80 attoseconds, decaying into two photons. Quantum chromodynamics (QCD), the theory of quarks and gluons, predicts this decay and the associated lifetime using the mechanism of broken chiral symmetry—the so-called chiral anomaly. Measuring the lifetime to high precision then provides a benchmark for theories that aim to improve on this original prediction. Larin *et al.* measured this lifetime with an uncertainty that was half that of the previous most precise result (see the Perspective by Meyer). The measured value was consistent with the original QCD prediction and less consistent with other theoretical approaches.

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