NUCLEAR PHYSICS

π^0 decay precision-tests the chiral anomaly

More precise neutral pion lifetime measurements probe quantum symmetry breaking

By **Harvey B. Meyer**

Most subatomic particles are strongly interacting composites called hadrons. Most hadrons are unstable and decay on extremely short time scales (10^{-22} s) to lighter hadrons. The electrically neutral pion, π^0, is the lightest hadron and decays on a time scale of 10^{-16} s in 98.8% of cases into two photons, $\gamma\gamma$, through the electromagnetic interaction. Historically, understanding this time scale presented a major challenge to theoreticians. On page 506 of this issue, Larin *et al.* (*1*) report that the measurement of the lifetime of the neutral pion has reached a precision of 1.5% through the combined results of the PrimEx-I and -II experiments. Its dominant decay to two photons proceeds mainly through the chiral anomaly, and calculating its decay time represents an important test of quantum chromodynamics in its low-energy, nonperturbative regime.

In the 1960s, it was realized that the multitude of hadron species could be understood economically in terms of more elementary degrees of freedom: the quarks. This simpler and deeper description is similar in nature to the understanding of the properties of the chemical elements in terms of the electronic structure of atoms. In the early 1970s, it became understood that the force that binds quarks into hadrons is mediated by a set of gauge fields. Quantum chromodynamics is the fundamental quantum field theory that describes this type of interaction.

The underlying cause of the short π^0 lifetime was found in 1969 with the discovery of the so-called chiral anomaly (*2*, *3*). Up to that point, it was assumed that a symmetry of the classical Lagrangian would protect π^0 from decaying in the limit of massless up and down quarks and lead to a longer lifetime. However, it turns out to be impossible to regularize quantum chromodynamics without breaking that symmetry. Therefore, the latter is not respected by the quantum fluctuations of the quantum chromodynamics fields and does not protect π^0 from decaying.

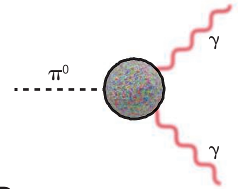
The quantum origin of the symmetry breaking leads to an exact prediction for the strength of π^0 coupling to $\gamma\gamma$ and hence the π^0 lifetime in the limit of massless up and down quarks. The product of the π^0 lifetime and the charged pion π^+ lifetime, which decays through the weak interaction, depends on no hadronic quantity other than the pion masses (see the figure). The matrix element of the divergence of the axial current, $\partial \cdot j_A$, between the vacuum and a $\gamma\gamma$ state can be calculated exactly and depends only on the fine-structure constant and the photon momenta. However, the matrix element is saturated by the exchange of a π^0, which the axial current j_A creates proportionally to the amplitude for the π^+ decay into the charged muon μ^+ and the muon neutrino ν_μ. Thus, in order for the two evaluations of the matrix element to be consistent, the coupling of π^0 to $\gamma\gamma$ must be inversely proportional to the π^+ decay amplitude.

A major objective of the measurement of the neutral pion lifetime by the PrimEx collaboration was to test its prediction at the percent level. With an overall precision of 1.5%, this goal has been reached. At this precision level, refinements must be applied to the prediction. They have been worked out by several groups and found to be on the order of +4.5 ± 1.0% (*4*). One of the most sophisticated theory predictions (*5*) obtains 8.04 (±0.11) × 10^{-17} s for the π^0 lifetime. Adding statistical and systematic errors in quadrature, this amounts to a tension of 1.8 standard deviations versus the combined result of the PrimEx-I and -II experiments, 8.34 (±0.13) × 10^{-17} s. Although this difference could be a statistical fluctuation, it provides motivation to revisit the theory prediction. The $\gamma\pi \rightarrow \pi\pi$ reaction also has a sharp low-energy prediction based on the chiral anomaly (*6*, *7*) and is being investigated by the COMPASS experiment (*8*).

The $\gamma\gamma$ decay width of π^0 has recently been evaluated from first principles using lattice quantum chromodynamics simulations (*9*). This numerical result is in agreement with the experimental measurement, but with its full uncertainty of 7%, it does not yet have the precision to clarify the above-mentioned tension between theory and experiment. Still, lattice quantum chromodynamics calculations have the potential to improve in the near future. The π^0-$\gamma\gamma$ coupling allows the two photons to scatter off each other through formation of the π^0 resonance. "Scattering of light by light" is one of the virtual processes that cause the magnetic dipole moment *g* of the muon to deviate from 2. This process is one of the leading sources of uncertainty in the predicting $(g - 2)_\mu$, whose measurement serves as a precision test of the standard model of particle physics (*10*). Therefore, the new precision measurement of the pion lifetime by Larin *et al.* contributes to consolidating the standard model prediction of this important quantity. ■

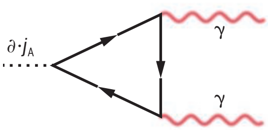
Limits on a lifetime

The neutral pion π^0 lifetime measured by Larin *et al.* can be compared to the calculated lifetime, which depends on the matrix element illustrated below.



Decay process

The Feynman diagram is shown for the decay amplitude of π^0 into two photons γ.



Strength of π^0-$\gamma\gamma$ coupling

The matrix element of the divergence of the axial current, $\partial \cdot j_A$, between the vacuum and a $\gamma\gamma$ state can be calculated exactly from this triangle diagram.

GRAPHIC: A. KITTERMAN/*SCIENCE*

Institute for Nuclear Physics, University of Mainz, 55099 Mainz, Germany. Email: meyerh@uni-mainz.de

REFERENCES AND NOTES

1. I. Larin *et al.*, *Science* **368**, 506 (2020).
2. S. L. Adler, *Phys. Rev.* **177**, 2426 (1969).
3. J. Bell, R. Jackiw, *Nuovo Cim. A* **60**, 47 (1969).
4. A. M. Bernstein, B. R. Holstein, *Rev. Mod. Phys.* **85**, 49 (2013).
5. K. Kampf, B. Moussallam, *Phys. Rev. D* **79**, 076005 (2009).
6. J. Wess, B. Zumino, *Phys. Lett. B* **37**, 95 (1971).
7. E. Witten, *Nucl. Phys. B* **223**, 422 (1983).
8. COMPASS Collaboration, J. M. Friedrich, *EPJ Web Conf.* **199**, 01016 (2019).
9. A. Gérardin, H. B. Meyer, A. Nyffeler, *Phys. Rev. D* **100**, 3034520 (2019).
10. F. Jegerlehner, *The Anomalous Magnetic Moment of the Muon* (Springer, 2017).

ACKNOWLEDGMENTS

H.B.M.'s work is supported by the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation program through grant agreement 771971-SIMDAMA.

10.1126/science.aba8063

Science

π^0 decay precision-tests the chiral anomaly

Harvey B. Meyer

Science **368** (6490), 469.
DOI: 10.1126/science.aba8063

Science (print ISSN 0036-8075; online ISSN 1095-9203) is published by the American Association for the Advancement of Science, 1200 New York Avenue NW, Washington, DC 20005. The title *Science* is a registered trademark of AAAS.