

A Quantum Cyclotron for Antimatter

A device that stores a single positron and controls its quantum states could measure its magnetic moment with unprecedented precision, testing a symmetry principle central to quantum field theory.

By **Paolo Crivelli**

Nearly 80 years ago, the discovery of an anomaly in the magnetic moment of the electron played a key role in the birth of quantum electrodynamics (QED). The electron magnetic moment has since become one of the most precisely measured properties of an elementary particle, providing stringent tests of the standard model of particle physics. The demonstration of an apparatus for measuring the magnetic moment of the electron's antiparticle—the positron—could enable new and exceptionally precise fundamental tests. Now a team led by Gerald Gabrielse of Northwestern University in Illinois has realized the first one-positron quantum cyclotron, which can store an individual positron while manipulating its quantized cyclotron and spin states [1]. This achievement opens a path toward a 30-fold

improvement in the measurement precision for the positron magnetic moment. Comparing the electron and positron magnetic moments would provide an exceptionally stringent test of *CPT* symmetry—a cornerstone of quantum field theory (QFT).

The use of particle magnetic moments as fundamental-physics probes started in 1947, when John Nafe, Edward Nelson, and Isidor Rabi measured the hyperfine splitting of hydrogen and deuterium and found a small discrepancy with predictions based on Dirac's theory of the electron [2]. Later that year, Polykarp Kusch and Henry Foley obtained direct evidence for this anomaly [3], while Willis Lamb and Robert Retherford's discovery of the Lamb shift in hydrogen [4] provided another indication that Dirac's theory was incomplete. The Dirac equation predicts a magnetic g factor (which relates a particle's magnetic moment to its angular momentum) of exactly 2 for a point-like electron, but quantum fluctuations shift this value slightly. In 1948, Julian Schwinger calculated the leading-order quantum correction: $a_e \equiv (g_e - 2)/2 = \alpha/2\pi$, where α is the fine-structure constant [5]. His result was in striking agreement with experiment and became an early landmark success of QED.

The race between experiment and theory was on. In 1966, the first direct measurement of the free positron's g factor confirmed its agreement with that of the electron to roughly 10 parts per million [6]. Meanwhile, theorists built on Schwinger's leading-order result, calculating the QED prediction for the electron's magnetic-moment anomaly to progressively higher orders. These efforts eventually reached fifth order in α/π , with the fifth-order contribution alone

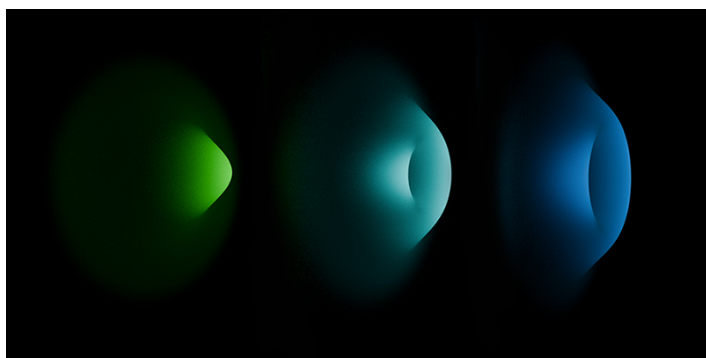


Figure 1: Radial probability distributions for a positron in the different quantum states of its cyclotron motion: ground state (left), first excited state (center), and second excited state (right). Credit: G. Gabrielse and L. Soucy/Northwestern University

requiring the evaluation of more than 12,000 Feynman diagrams [7].

This comparison tests something deeper than QED: *CPT* invariance. The *CPT* theorem states that any local, Lorentz-invariant QFT satisfying certain standard assumptions must remain unchanged under *CPT*. One consequence is that particles and their antiparticles must have magnetic moments equal in magnitude and opposite in sign—and hence identical *g* factors. A confirmed difference between the electron and positron *g* factors would challenge the very foundations of local relativistic QFT.

A broader motivation for seeking differences between particles and antiparticles stems from the dominance of matter over antimatter in the Universe, which in some theoretical scenarios could be related to *CPT* violation. Tests of *CPT* symmetry now include comparisons of protons with antiprotons and of hydrogen with antihydrogen, as well as precision studies of positronium—the bound state of an electron and a positron.

A major advance in magnetic-moment precision came with the development of Penning-trap techniques. By combining magnetic and electric fields, a Penning trap can confine a single charged particle for months. The magnetic field defines both the particle's cyclotron motion and the splitting of its spin states. Measuring the cyclotron frequency ω_c and the spin-precession frequency ω_s , and hence their difference $\omega_a = \omega_s - \omega_c$, directly determines the anomalous magnetic moment: $a_e = (g_e - 2)/2 = \omega_a / \omega_c$.

Over decades, Penning-trap experiments evolved into the one-electron quantum cyclotron, which can resolve individual jumps between a single electron's quantized cyclotron states as well as flips between its spin states. These transitions provide access to ω_c and ω_s , respectively. The technique has pushed measurements of the electron *g* factor to a precision of 0.13 parts per trillion [8].

Measurements for the positron, however, have not kept pace. The most precise electron-positron comparison to date comes from a 1987 experiment, which found the two *g* factors equal within 2.1 parts per trillion [9]. Until now, the spectacular advances made possible by the one-electron quantum cyclotron have had no positron counterpart. The main

challenge has been getting a positron into the exceptionally well-isolated environment required for the measurement.

Gabrielse and his colleagues obtain positrons from a radioactive sodium-22 source, which emits kinetic energies of up to 546 kilo-electron-volts. These positrons must be slowed and cooled until a single particle can be captured in a trap maintained at 300 mK. That temperature corresponds to a thermal energy of just 26 micro-electron-volts—more than 10 orders of magnitude below the positrons' maximum initial energy. At this temperature, thermal photons capable of exciting the positron are virtually absent, allowing it to remain in its lowest cyclotron state until a transition is deliberately induced.

Loading the positron cannot be accomplished simply by creating a large opening in the trap: The trap electrodes form a nearly closed, high-quality microwave cavity, and an opening would degrade its ability to suppress spontaneous emission. In the experiment's 5.6-tesla magnetic field, the positron's cyclotron frequency is about 156 GHz. At that frequency, an excited cyclotron state would decay in free space in just 83 milliseconds—too quickly for reliable nondestructive detection. Inside the cavity, by contrast, the state's lifetime is extended to about four seconds.

Gabrielse and his collaborators solve the loading problem through an ingenious use of positronium. After being slowed in a tungsten moderator, a positron can capture an electron, forming an excited, electrically neutral positronium atom. The positronium passes through a tiny (625- μ m-diameter) aperture in the otherwise nearly closed microwave cavity. Once inside, the trap's electric field ionizes the atom: the electron escapes, while the positron remains trapped. Positronium—usually the subject of high-precision experiments—plays a different role here: Because it is electrically neutral, it can carry the positron “undercover” into the trap.

Loading a single positron currently takes 8–11 hours. Once captured, it remains trapped for months. The researchers cool its cyclotron motion into the quantum ground state and then use microwaves to drive individual transitions between cyclotron levels (Fig. 1). They read out the resulting state nondestructively using a magnetic-field gradient known as a magnetic bottle. Each added cyclotron quantum shifts the

positron's axial oscillation frequency by about 3.8 Hz. Tracking these frequency shifts allows the researchers to resolve individual cyclotron quantum jumps and spin flips of a single positron—the essential ingredients for quantum-jump spectroscopy of its magnetic moment.

The team's demonstration is an experimental breakthrough: A single positron can now be loaded, cooled, stored for months, manipulated one quantum at a time, and read out nondestructively. But it does not yet provide a high-precision measurement of the positron g factor. Achieving such a measurement will require detailed spectroscopy and exquisite control of systematic effects.

The quantum cyclotron is not the only game in town. Researchers at the Max Planck Institute for Nuclear Physics in Germany are developing a different approach [10]. Their Lepton Symmetry (LSym) experiment aims to compare the electron and positron magnetic moments to 14 digits of precision by trapping a positron alongside a hydrogen-like helium-4 ion, whose sole bound electron provides the electron reference. Simultaneously trapping both species makes magnetic-field fluctuations common to both measurements, largely canceling out this source of noise. The measured frequencies can then be combined with the particles' known charges and masses to compare their g factors.

The two approaches thus pursue precision in complementary ways. The quantum cyclotron aims to bring a standalone measurement of the positron's magnetic moment to the precision already achieved for the electron; LSym is designed for a simultaneous particle–antiparticle comparison. Together, they could test the equality of the electron and positron

magnetic moments to well below one part per trillion. If they succeed, a comparison first made 60 years ago could enter an entirely new precision regime, subjecting *CPT* symmetry to unprecedented scrutiny.

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