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Cavity Control in a Single-Electron Quantum Cyclotron: An Improved Measurement of the Electron Magnetic Moment

Abstract

A single electron in a quantum cyclotron yields new measurements of the electron magnetic moment, given by $g/2 = 1.001\,159\,652\,180\,73\,(28)$ [0.28 ppt], and the fine structure constant, $\alpha^{-1} = 137.035\,999\,084\,(51)$ [0.37 ppb], both significantly improved from prior results. The static magnetic and electric fields of a Penning trap confine the electron, and a 100 mK dilution refrigerator cools its cyclotron motion to the quantum-mechanical ground state. A quantum nondemolition measurement allows resolution of single cyclotron jumps and spin flips by coupling the cyclotron and spin energies to the frequency of the axial motion, which is self-excited and detected with a cryogenic amplifier.

The trap electrodes form a high-Q microwave resonator near the cyclotron frequency; coupling between the cyclotron motion and cavity modes can inhibit spontaneous emission by over 100 times the free-space rate and shift the cyclotron frequency, a systematic effect that dominated the uncertainties of previous g-value measurements. A cylindrical trap geometry creates cavity modes with analytically calculable couplings to cyclotron motion. Two independent methods use the cyclotron damping rate of an electron plasma or of the single electron itself as probes of the cavity mode structure and allow the identification of the modes by their geometries and couplings, the quantification of an offset between the mode and electrostatic centers, and the reduction of the cavity shift uncertainty to sub-dominant levels. Measuring g at four magnetic fields with cavity shifts spanning thirty times the final g-value uncertainty provides a check on the calculated cavity shifts.

Magnetic field fluctuations limit the measurement of g by adding a noise-model dependence to the extraction of the cyclotron and anomaly frequencies from their resonance lines; the relative agreement of two line-splitting methods quantifies a line-shape model uncertainty.

New techniques promise to increase field stability, narrow the resonance lines, and accelerate the measurement cycle.

The measured g allows tests for physics beyond the Standard Model through searches for its temporal variation and comparisons with a "theoretical" g-value calculated from quantum electrodynamics and an independently measured fine structure constant.