Colloquium

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

Measurements of the electron magnetic moment (the "g-value") probe the electron's interaction with the fluctuating vacuum. With a quantum electrodynamics calculation, they provide the most accurate determination of the fine structure constant. Comparisons with independent determinations of the fine structure constant are the most precise tests of quantum electrodynamics and probe extensions to the Standard Model of particle physics.

I will present two new measurements of the electron magnetic moment. The second, at a relative uncertainty of 0.28 parts-per-trillion, yields a value of the fine structure constant with a relative accuracy of 0.37 parts-per-billion, over 10-times smaller uncertainty than the next-best methods.

The high precision arises from the combination of many useful techniques. A single-electron quantum cyclotron, so-called because a quantum nondemolition measurement resolves the lowest cyclotron and spin levels, is held in a cylindrical Penning trap, whose well-understood cavity-mode structure inhibits spontaneous emission and creates calculable frequency shifts due to electron–cavity coupling. A low temperature (100 mK) narrows the linewidths of the measured frequencies and inhibits stimulated absorption in the cyclotron motion, effectively locking it in the quantum ground state. The signal from the electron's axial motion is fed back as a drive, forming a single-particle self-excited oscillator and increasing the signal-to-noise.

Lecture 1

Entangled Mechanical Oscillators and a Programmable Quantum Computer: Adventures in Coupling Two-Level Systems to Quantum Harmonic Oscillators

The two-level system and the harmonic oscillator are among the simplest analyzed with quantum mechanics, yet they display a rich set of behaviors. Quantum information science is based on manipulating the states of two-level systems, called quantum bits or qubits. Coupling two-level systems to harmonic oscillators allows the generation of interesting motional states.

When isolated from the environment, trapped atomic ions can take on both of these behaviors. The two-level system is formed from a pair of internal states, which lasers efficiently prepare, manipulate, and read-out. The ions' motion in the trap is well described as a harmonic oscillator and can be cooled to the quantum ground state.

In this lecture, I will describe a complete set of methods for scalable ion trap quantum information processing and their use in a programmable two-qubit quantum processor. The qubits are stored in two beryllium hyperfine states that are insensitive to magnetic field fluctuations. They have coherence times hundreds of times longer than a typical experiment lasts. Two beryllium ions are stored simultaneously with two magnesium ions, which allow recooling the ions' motion without destroying any quantum information. Segmented trap electrodes allow separation of parts of the ion chain for quantum information transport and for individual laser-addressing for single-qubit gates. An arbitrary quantum operation on two qubits can be described with 15 real numbers, and we implement a quantum circuit composed of one and two-qubit gates with sufficient input parameters that it can be programmed to implement any operation.

Along the way, we use some of the above techniques to entangle spatially separated mechanical oscillators, consisting of the vibrational states of two pairs of ions held in different locations.

Lecture 2

Optical Atomic Clocks

The most precise measurement techniques involve time, frequency, or a frequency ratio. For example, for centuries, accurate navigation has relied on precise timekeeping – a trend that continues with today's global positioning system. After briefly reviewing the current microwave frequency standards based on the hyperfine structure of cesium, I will describe work towards atomic clocks working at optical frequencies. Among these are standards based on trapped ions or on neutral atoms trapped in an optical lattice. A frequency comb allows the comparison of different optical frequencies and the linking of optical frequencies to more-easily-counted microwave ones. Though still in the basic research stage, optical clocks have already made significant contributions to physics by setting limits for time-variation of the fundamental constants, seeing general relativistic effects at the centimeter scale, and testing local position invariance by looking for differential redshifts as the Earth moves in the Sun's gravitational potential.

Lecture 3

High-Energy Physics with Low-Energy Symmetry Studies

Discrete symmetries – charge conjugation (C), parity inversion (P), time reversal (T), and their combinations – provide insight into the structure of our physical theories. Many extensions to the Standard Model predict symmetry violations beyond those already known. From the first evidence of P-violation in the 1950s using cold atoms, low-energy, high-precision experiments have quantified existing violations and constrained further ones. In this lecture, I will describe several searches for discrete symmetry violations with low-energy experiments. T-violation, closely related to matter/antimatter asymmetry through the CPT theorem, is tightly constrained by searches for intrinsic electric dipole moments. CPT-violation – the only combination of these symmetries obeyed by the entire Standard Model – is constrained in leptons by comparisons of the electron to the positron and in baryons by comparisons of the proton to the antiproton. Ongoing work with antihydrogen aims to further constrain CPT-violation in both these sectors.