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QUANTUM OPTICS

A shift on a chip

Douglas H. Bradshaw and Peter W. Milonni

The Lamb shift, a minute change in certain energy levels of quantum systems that was first measured in atomic hydrogen some 60 years ago, has now been observed in a solid-state superconducting system.

The emission and absorption of light by atoms can be significantly affected by their environment. For many years, physicists have studied how atoms behave in cavities that confine light and restrict the frequencies with which the atoms interact. Cavity quantum electrodynamics (cavity QED) experiments, which examine how light and matter interact in a cavity, can be designed such that an atom is well described as a two-state system (or 'qubit') interacting with a single light frequency in a nearly lossless cavity. It has been observed, for instance, that the frequency of the light emitted (or absorbed) in an atomic transition can be altered by a cavity. More recently, similar effects have been observed in circuit QED, in which pieces of solid-state superconducting systems acting as qubits are embedded in on-chip circuits that are, in effect, one-dimensional cavities[1,2]. Writing in *Science*, Fragner *et al.*[3] now report experiments in which one of the most studied effects of QED in atomic physics — the Lamb shift — has been measured in circuit QED (Fig. 1).

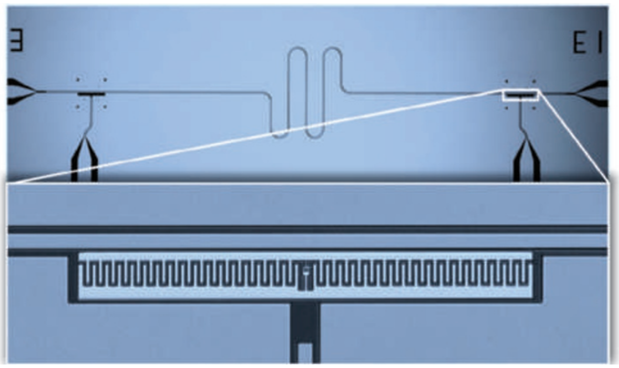

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Figure 1 | Lamb shift on a solid qubit. The image shows the resonator (top) used in the experiments of Fragner *et al.*[3] to detect a tiny shift in the transition frequency — the Lamb shift — of a solid-state superconducting qubit (bottom). The qubit of dimensions 0.3 mm × 30 μm is embedded in the resonator at the position indicated by the boxed area (top right). (Image taken from ref. 1.)

The Lamb shift in atomic hydrogen was famously measured some 60 years ago[4]. Experiments showed that, in a vacuum, one of the atom's energy levels is shifted very slightly from the value predicted when the effect on the electron of the electromagnetic vacuum is ignored. The corresponding shift in the frequency of the transition of the electron to the ground state, relative to the unshifted frequency (ν), is only about 4×10^{-7}. This shift can be attributed largely to the interaction of the hydrogen atom with a continuum of electromagnetic frequencies, all in the vacuum state. Quantum fluctuations of this vacuum field, associated with the emission and absorption of 'virtual' photons, cause the electron to undergo fluctuations that change its energy level from that predicted when it is assumed to interact only with the nucleus.

But cavity QED has allowed for conceptually simpler experiments in which atoms interact with only one electromagnetic-field frequency. If this frequency is exactly tuned to the atomic resonance, a quantum of energy can flow back and forth between an atom and the electromagnetic field at a rate known as the Rabi frequency (Ω). By introducing a 'detuning' (Δ) between the atomic-transition frequency and the field frequency, one can change the nature of the atom–field interaction. When the ratio Δ/Ω is large, the observable effect of the field on the atom is to shift the atomic-transition frequency rather than to cause energy to oscillate to and fro between the atom and the field. The shift is proportional to $(q+1/2)/\Delta$, where q is the number of photons in the cavity. The Lamb shift occurs when the cavity is devoid of photons ($q=0$), and is thus associated with quantum fluctuations of the vacuum state of the field. This Lamb shift for a two-state atom was first measured in a cavity QED experiment[5]; Lamb shifts amounting to about $10^{-8}\,\nu$ were measured for the smallest detunings.

In circuit QED, a qubit is a superconducting two-state system based on the Josephson junction — two superconductors separated by a thin insulator across which electron pairs can tunnel. In the very simplest approximation, two parallel junctions can form a qubit with a transition frequency controllable by a magnetic field. The cavity resonator in circuit QED is effectively a one-dimensional waveguide formed by a superconducting structure patterned on a silicon chip. An electromagnetic field in such a resonator induces transitions in a qubit inside it if its frequency is close to the qubit transition frequency. Then the system can be described in much the same way as a qubit interacting with a single field frequency in cavity QED.

In their experiments, Fragner and colleagues[3] measured ν and the qubit–field coupling constant, which describes the strength of the interaction and thus determines the Lamb shift. They then determined the Lamb shift from the difference between ν and the measured, shifted qubit transition frequency. The detuning was varied by changing the magnetic flux through the qubit circuit. For the largest detunings, the authors obtained an excellent fit of the measured Lamb shifts to the simplified theoretical predictions based on the two-state model of the parallel Josephson junctions; a more accurate theory that accounts for deviations of the Josephson pair from a two-state system gave an excellent fit for all detunings.

A notable difference between these Lamb shifts and those in cavity QED is their magnitude — approximately $0.014\,\nu$ at the smallest detunings. These relatively large shifts reflect a strong qubit–field interaction resulting from the large electric dipole moment characterizing the qubit as well as the large vacuum-field strengths possible in the micrometre-scale resonators used in circuit QED. The strong coupling (large Rabi frequency) inferred from the Lamb-shift experiments directly illustrates one reason for the growing interest in circuit QED in connection with quantum computing[6–8], which requires that information between a photon and a qubit be exchanged rapidly compared with the rates at which any other effects, such as the escape of the photon from the resonator, cause information about the qubit state to be lost. ■

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