Observation of macroscopic quantum coherence using new type of superconducting circuit.

A. Fluxonium: single Cooper pair circuit free of charge offsets.

Authors: V. E. Manucharyan, J. Koch, L. I. Glazman, and M. H. Devoret

http://arxiv.org/abs/0906.0831v2 ; Science **326**, 113-116 (2009).

B. Coherent oscillations between classically separable quantum states of a superconducting loop

Authors: V. E. Manucharyan, J. Koch, M. Brink, L. I. Glazman, and M. H. Devoret

http://arxiv.org/abs/09010.3039v1 .

Recommended with a Commentary by Bertrand I. Halperin, Harvard University.

These papers report the development of a new type of superconducting quantum device, named "fluxonium" with some highly desirable new features, and experiments which demonstrate the power of the device by using it to observe, "for the first time", coherent quantum tunneling between two "classically distinct" states of a superconducting circuit. This application also required clever design of a measuring scheme, which can both sense the state of the quantum device, and reset the state when desired. These are impressive achievements, which suggest that the new device may have great potential for applications in quantum measurements and computation.

A schematic circuit representation of the fluxonium device is shown in the left hand portion of Fig 1, labeled "atom". If we neglect the coupling to the external world through the capacitance C_c, the device may be represented by a Hamiltonian of the form

$$H = 4E_C(N - N_0)^2 + \frac{E_L}{2}\left(\phi + 2\pi\Phi_{ext}\right)^2 - E_J \cos\phi \,, \qquad (1)$$

where ϕ is the phase change across the small Josephson junction indicated by the X in the figure; Φ_{ext} is the external magnetic flux through the circuit, in units of the superconducting flux quantum $\Phi_0 \equiv h/2e$; the operator N measures the charge-difference stored on the junction capacitance C_J; and N_0 is an "offset charge", reflecting the potential due to any external charges in the vicinity. The charging energy is defined as $E_C = e^2/2C_J$, and the charge operator N is defined in units of $2e$, so that it satisfies the commutation

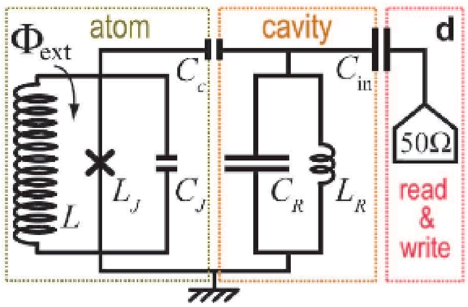

Figure 1. Equivalent circuit for device used in Article B to study coherent quantum tunneling.

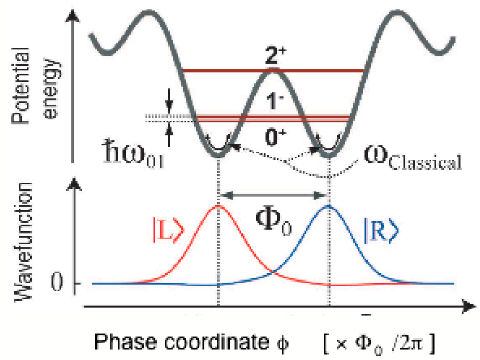

Figure 2. Potential energy and wave function with $\Phi_{ext} = \Phi_0/2$.

rule $[\phi, N] = i$. The coefficient E_J is the Josephson coupling energy, while $E_L = (\hbar/2e)^2/L$, where L is an effective inductance of the circuit.

The reason the Hamiltonian can be reduced to the simple form (1) is that the entire circuit is superconducting, and the temperature is sufficiently far below the energy gap that quasiparticle excitations can be neglected, and the circuit has been designed so that parasitic elements, which would complicate the Hamiltonian, have been largely eliminated.

A major innovation of the fluxonium design is that it achieves a large value of L by using the kinetic inductance produced by a series array of of $N_L = 43$ large Josephson junctions. The Josephson coupling energy E_J^A and the capacitance for each of these junctions are sufficiently large that one can neglect the possibility of phase slips through them, Then, if the wire between the junctions is sufficiently thick, the total energy of the array is minimized when the phase difference across each of the large junctions is equal to $(\phi + 2\pi\Phi_{ext})/N_L$. The energy of the array then has the form of the second term in (1), with $E_L = E_J^A/N_L$. This in the end, is small compared to the coupling energy E_J of the "small junction" shown in Fig. 1. (The magnetic flux produced by supercurrent in the circuit may be neglected, as it is always $\ll \Phi_0$.)

The parameters quoted in article B are $E_L/h = 0.52$ GHz, $E_J/h = 8.9$ GHz, and $E_C/h = 2.4$ GHz. The authors note that no previous device achieved a combination of parameters in this range. They also note that if L had been obtained simply from the electromagnetic interaction of a current-carrying superconducting loop with its generated magnetic field, the associated distributed capacitance would have led to a value of the ratio E_C/E_L comparable to the square of fine structure constant, rather than to a value ≥ 1, as achieved in this device.

Note that the phase ϕ in Eq. (1) is defined on the entire real line, and H is not periodic in ϕ. The conjugate variable N is also defined on the real line, and is not required to be an integer. Thus ϕ plays the role of a coordinate, and N plays the role of momentum, in a standard one-dimensional Schrödinger equation. An important property of H is that its eigenvalues are completely independent of the offset charge N_0, which makes the fluxonium device highly insensitive to low-frequency charge fluctuations in the environment.

The upper panel of Fig. 2 shows the effective potential for the variable ϕ and the energies of the three lowest quantum states, when the external flux is tuned to the symmetric point $\Phi_{ext} = \Phi_0/2$, and the parameters E_J, E_C, E_L have the values stated above. The lower panel shows the wave functions of states $|L\rangle$ and $|R\rangle$, which are the approximate ground states localized in the the left or right wells, respectively. As illustrated, the states have a separation that is large compared to their widths, so the states may be considered classically separable.

The actual energy eigenstates, labeled 0 and 1, are even and odd linear combinations of the two localized states, with a frequency splitting $\omega_{01}/2\pi \approx$ 350 MHz that is small compared to the classical oscillation frequency in a single well ($\approx$ 13.5 GHz). The third energy level, labeled 2, which is spread across both wells, has a much higher energy, with the frequency separation $\omega_{02}/2\pi \approx 10$ GHz.

If the system is prepared initially in one of the localized states, say $|L\rangle$, we would expect it to oscillate back and forth between the two wells at the frequency ω_{01}, due to resonant tunneling between the wells. Ideally, one would like to observe this by a direct measurement of the expectation value of the phase ϕ as as a function of time. However, the electrical currents associated with different values of ϕ are much too small to measure, so an alternative scheme was necessary. The observations in article B were achieved by using a weak capacitive coupling to a quater-wave trasmission-line resonator, (the "cavity" in Fig. 1), whose frequency is close to the large excitation frequency ω_{02}. By detecting a small phase shift in a signal applied to the transmission line at the resonant frequency, the experimenters could distinguish between situations where the fluxonium circuit is in one or the other of the eigenstates

0 or 1. By applying a second signal at the coherent tunneling frequency ω_{01}, they could then observe oscillations between the states 0 and 1 at a Rabi frequency governed by the strength of this second signal. (The authors present a figure with ten such oscillations). Moreover, by applying a signal which is slightly detuned to the red or the blue from ω_{02}, the authors are able to reset the fluxonium, at will, to the state 0 or 1. Finally, the authors were able to study the coherence of the macroscopic coherent tunneling oscillations, using a Ramsey fringe protocol. They obtain a quality factor $Q \equiv T_R \omega_{01} = 580$, where T_R is the Ramsey decay time. Large values of Q are important for applications such as quantum computation.

Article B notes, in its introduction, that the experimental realization of macroscopic quantum coherence between classically distinct states of a superconducting circuit, proposed by Leggett in 1980 [1,2], has long been understood to be difficult and perhaps believed impossible. According to the authors, their experiment is the first to achieve this goal, because theirs is the first in which the wave functions of the states have a difference in the mean value of ϕ that is large compared to the fluctuations in each state. An important motivation for Leggett's original interest in such experiments was as a test of the validity of quantum mechanics itself, in a new regime where he felt there was a possibility that discrepancies might be found. I am not able to say how far the current experiments have carried us in the direction that Leggett envisaged in his paper. It is clear, however, that the experiments have demonstrated the capabilities of an exciting new device with great promise in the area of quantum coherence and manipulation.

References.

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[2]. A. J. Leggett, "Testing the limits of quantum mechanics: motivation, state of play, prospects," J. Phys.: Condensed Matter **14**, R415 (2002).