Superconducting Artificial Atom

Quantum mechanics was developed initially to describe properties of electrons in atoms which could not be explained by the classical laws of physics. During the last decade, nanometre scale superconducting electrical circuits incorporating tunnel junctions for the superconducting electrons (Josephson junctions) have revealed puzzling properties at very low temperature that deviate from the classical laws of macroscopic electricity. Quantum mechanics is needed to describe the current and voltage behaviour of these circuits. Contrary to the hydrogen atom in which the wavefunction describes a single electron, in the superconducting circuit one has a macroscopic quantum state of all the superconducting electrons. However, because there are certain similarities to atoms, such as the quantization of energy levels, superposition of quantum states, and the interaction with an electromagnetic field, we call these circuits "artificial atoms".

The interesting feature of such an "artificial atom" is that its characteristics are not rigid as in a real atom but controllable by the experimentalist. Indeed, they are not defined by a fixed number of electrons and protons as in a real atom but by properties of the circuit (its capacitance, inductance, tunnel barrier). These are adjustable during the nano-fabrication process. In addition, the artificial atom's quantum states can be readily manipulated by external magnetic flux or microwaves.

Currently, most of the superconducting artificial atoms studied are described by a single, anharmonic quantum oscillator. For instance, this is realized by circuits containing a single Josephson tunnel junction. The equivalent circuit is an "LC" electrical resonator, made up of a capacitance C and a non-linear inductance L associated with the Josephson junction. The total energy of the superconducting electrons is quantized. (When only the two first levels are considered, the artificial atom can act as a "quantum bit").

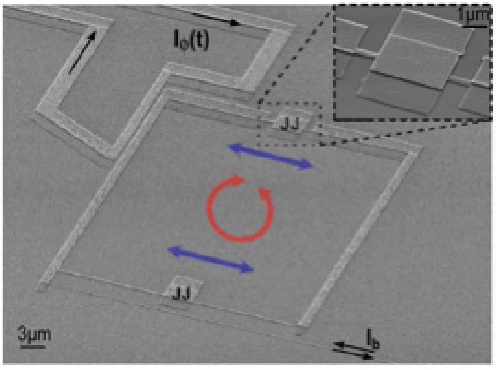

Figure 1: Scanning Electron Microscope image of a superconducting "artificial atom". It consists of a highly inductive loop of aluminium wire with two Josephson tunnel junctions (JJ) made by two overlapped Al layers separated by a thin aluminium oxide layer (see zoom top right). The circuit is superconducting below 1.5K and the quantum experiments are realized at 40mK. The modes "s" and "a" (schematized by blue and red arrows, respectively) are excited by applying external microwave currents $I_\Phi(t)$ or $I_b(t)$.

In our own recent work, we have studied a circuit with *two* tunnel junctions (see Fig. 1), producing a new type of artificial atom described by two strongly coupled anharmonic oscillators. This leads to two modes labelled "s" (symmetric) and "a" (anti-symmetric) because the current oscillations at each junction can be either in-phase or in phase-opposition, respectively.

We apply a variable frequency microwave flux through the circuit to induce excitations of the two modes and thus determine their quantized energy level spectrum. Furthermore, we can tune the energies of the quantized states by applying an external magnetic field. Fig. 2(a) gives the field-dependence of the transitions from the ground state |0a, 0s> to the first 4 excited states. In particular, the Figure shows an anti-crossing of two levels (dotted green square) which demonstrates a non-linear coupling between the two modes "s" and "a".

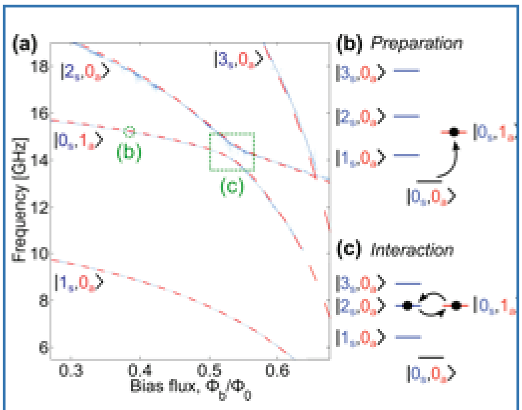

Figure 2: (a) Energy spectrum of the artificial atom of Fig. 1 versus applied magnetic flux (in units of the flux quantum Φ_0), from microwave spectroscopy (blue curves) and a theoretical fit (red curves). (b), (c); Quantized energy spectrum of the two anharmonic oscillators at (b) $\Phi=0.37\Phi_0$ and at (c) $\Phi=0.54\Phi_0$. In (b) the system is prepared in the state |0s, 1a> and in (c), following an ultrafast flux jump, coherent oscillations occur between states |0s, 1a> and |2s, 0a>, producing up and down frequency conversion.

In another experiment, the non-linear coupling between the two modes leads to coherent up and down frequency conversion, see Figs 2(b), 2(c). At $\Phi=0.54\ \Phi_0$, the state |0s, 1a> (one excitation at frequency 14.4 GHz in the anti-symmetric mode) evolves to the state |2s, 0a> (two excitations at about 7.2 GHz in the symmetric mode). The coherence of this process is demonstrated by the observation of free oscillations between the states |0s, 1a> and |2s, 0a> of the two modes.

The non-linear coupling terms observed in our artificial atom are orders of magnitude larger than those studied in atomic physics and non-linear optics, leading to new properties and also to a novel method for fast quantum "non-demolition" measurements.

CONTACTS

Olivier BUISSON
olivier.buisson@grenoble.cnrs.fr

Wiebke GUICHARD
wiebke.guichard@grenoble.cnrs.fr

Ph.D STUDENT
Florent LECOCQ

FURTHER READING

NON-LINEAR COUPLING BETWEEN THE TWO OSCILLATION MODES OF A DC-SQUID
F. Lecocq, J. Claudon, O. Buisson and P. Milman
Phys. Rev. Lett. 107, 197002 (2011).

COHERENT FREQUENCY CONVERSION IN A SUPERCONDUCTING ARTIFICIAL ATOM WITH TWO INTERNAL DEGREES OF FREEDOM
F. Lecocq, I. M. Pop, I. Matei, E. Dumur, A. Feofanov, C. Naud, W. Guichard, O. Buisson
Phys. Rev. Lett. 108, 107001 (2012).