Putting artificial atoms on the clock

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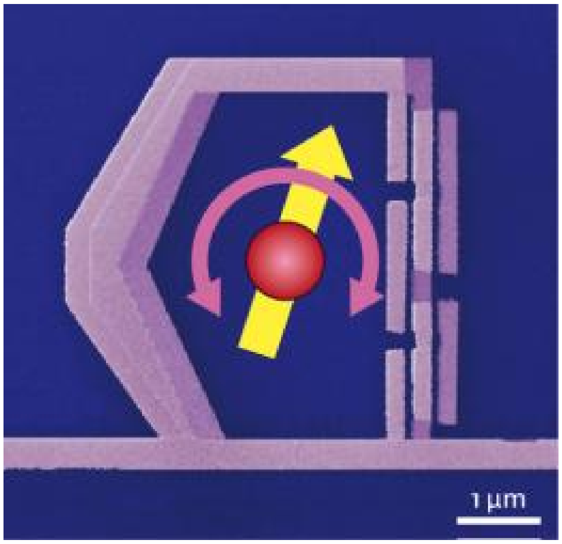

An electron micrograph of the artificial atom. A superconducting loop of metal is interrupted by non-superconducting Josephson junctions. The current can flow clockwise or counterclockwise around the loop, and are analogous to the electron spin of a real atom (yellow arrow). The horizontal wire along the bottom of the atom can be used to excite the atom, and to measure its emission. Credit: Reproduced, with permission, from Ref. 2 © 2010 AAAS

Around the turn of the century, scientists began to understand that atoms have discrete energy levels. Within the field of quantum physics, this sparked the development of quantum optics in which light is used to drive atoms between these energy levels. The resulting ability to control the behavior of solid-state systems with free-space light -- the former has discrete energy levels and the latter has continuously tunable energy -- yielded new fundamental science as well as new technology. Some of the applications that emerged include lasers, atomic clocks and quantum information processing.

Despite these successes, however, quantum optics researchers were traditionally constrained by their reliance on the use of real, or natural, atoms. In previous work, Jaw-Shen Tsai and colleagues at the RIKEN Advanced Science Institute and NEC, Japan, circumvented this constraint by demonstrating that an engineered solid-state device can reproduce many of the characteristics of the quantum optics work done on real atoms, including fluorescence and absorption. This suggested that the devices could be considered to be artificial atoms. Now, the researchers have reported in Physical Review Letters the first dynamic measurements of how their artificial atom interacts with light.

While real atoms are readily available and well understood, designing atoms from scratch gives experimentalists greater flexibility. It also lessens difficulties associated with trapping and integrating real atoms into complex systems. In addition, artificial atoms can be made to strongly interact with light, which makes possible highly integrated and scaled devices that exploit single-atom quantum optics. By comparison, it is difficult to achieve strong coupling between light in free space and a real atom; as a result, quantum optics work with real atoms requires many atoms, or highly concentrated light, making integration more difficult.

In place of real atoms, Tsai and his colleagues built a device that, on first glance, looks nothing like an atom: it consists of a loop of superconducting wire, about 16 micrometers in circumference, which is interrupted with four so-called ‘Josephson junctions’ that are not superconducting (Fig. 1). The relationship between the magnetic flux through the loop, and the current flowing around it, restricts the possible values of the current. Crucially, only certain amounts of current are allowed to flow around the device; so, like an atom, the energy levels of the device are discrete.

Rather than using free-space light to couple to their atom, the researchers built a thin wire along the bottom of their artificial atom. This wire, which can be modeled as a transmission line, supports electromagnetic waves, just as free space does. Unlike in free space, however, the researchers could carefully control the shape, energy and direction of the electromagnetic waves in the wire. Previously, Tsai and colleagues demonstrated that their artificial atom can scatter 94% of the power flowing down the wire, as a result of strong inductive coupling. This compares to, at most, a few percent scattering of a free-space photon by a real atom.

Going beyond showing that their artificial atom was able to mimic the behavior of real atoms under static conditions, Tsai and colleagues succeeded in demonstrating a precise measurement of how their artificial atom changes in time.

The researchers excited their artificial atom with a microwave field that was carried by the transmission line. Some of this driving field was absorbed by the atom and caused currents to flow around the superconducting loop. These currents could flow either clockwise or counterclockwise, with the two directions representing the two lowest-energy excited states of the atom. Because of the quantum nature of the atom, the actual current at any moment could be composed of a superposition of these counter-circulating currents: for example, a 20% counterclockwise rotation and an 80% clockwise rotation were possible. In a classic example of ‘quantum weirdness’, this was not the same as reducing the clockwise rotation by 20%—each current flowed independently and at the same time.

Tsai and colleagues could determine the degree of light absorbed by the device, and its characteristics, by monitoring the currents in the transmission line. In fact, by resolving different components of these currents, the researchers succeeded in building a complete picture of how the atom's excited state behaved: specifically, they could tell the amplitude of the two circulating currents, and the phase between them.

Measuring the strengths and phases of the currents circulating through the artificial atom is similar to a much more difficult measurement on a real atom: the measurement of the direction and strength of the magnetic moment of its electrons—or electron spin. Measuring electron spin is a current focus of research because it is both an important quantum system and has a variety of proposed applications, ranging from computing to sensing. The team's measurement on their artificial atom was made easier by the strong coupling possible between the atom and the electromagnetic fields in the adjacent transmission line.

This new research thus serves as another demonstration of the versatility and control afforded by artificial atoms, and it extends the analogy between real and artificial atoms into the domain of time. As a likely next step, Tsai says, his group will work on applying their artificial atom to quantum computing applications, which require a quantum bit, or 'qubit', with two or more discrete energy levels that they can place into a superposition and allow to evolve in time. Tsai and his team have proven their artificial atom is capable of doing exactly that.

More information: Astafiev, O., et al. Resonance fluorescence of a single artificial atom. *Science* 327, 840–843 (2010). www.sciencemag.org/content/327/5967/840.short

Abdumalikov, A.A., et al. Dynamics of coherent and incoherent emission from an artificial atom in a 1D space. *Physical Review Letters* 107, 043604 (2011). prl.aps.org/abstract/PRL/v107/i4/e043604

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