

***Strong Coupling of a Single Microwave Photon to a Superconducting Qubit
Using Circuit Quantum Electrodynamics***

by

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Introductory and Background Scientific Material

This paper reports the first experiment to coherently couple a single photon to a single superconducting qubit (quantum bit or artificial ‘atom’). The artificial ‘atom’ actually consists of roughly 1 billion aluminum atoms acting in concert like a single atom. The microwaves have a wavelength of about 1 cm and yet act like particles (photons). A single photon is absorbed and reemitted by the ‘atom’ some 12 million times per second leading to the formation of a novel quantum state that is partly photon and partly atom excitation. This represents a new paradigm in which quantum optics experiments can be performed in a micro-chip electrical circuit using microwaves instead of visible photons from lasers. In addition to being of fundamental interest, this new system has many desirable features as an architecture for developing quantum computers.

Classically, light consists of waves, but quantum mechanically its energy is carried by particles called photons that have peculiar wave-like properties. We are approaching the 100th anniversary of Einstein’s famous 1905 paper in which the existence of the photon

was postulated to explain the photoelectric effect (whose existence is the basis of digital cameras for example).

If an atom in free space is placed in an excited quantum state it will eventually spontaneously emit a photon and fall down to a lower energy state. This process is irreversible because the photon flies away from the atom at the speed of light never to return. After several decades of dedicated effort, atomic physicists have learned to alter this situation dramatically by placing the atom inside a cavity (constructed from highly reflecting mirrors) that traps the photon and allows it to be repeatedly absorbed and reemitted by the atom many times before it escapes the cavity. In this so-called 'strong-coupling' regime, the quantum state of the system becomes a peculiar coherent superposition of two simultaneous possibilities: the energy is either an excitation of the atom or is a photon. Quantum mechanics does not permit us to know which possibility actually occurs without destroying this delicate state.

The photons of visible light commonly emitted by lasers and light bulbs have extremely feeble energy (a small night light emits torrent of some 10^{15} photons per second but this still amounts to only about 1 watt of power). Nevertheless the energy of an individual photon is large enough to cause chemical reactions (such as those that allow your eye to detect light) and to trigger special detectors based on the photoelectric effect known as photomultipliers. Microwaves are a form of light but these waves oscillate at frequencies much lower than visible light. The microwaves used in the Yale experiment are in a similar frequency range to those used in cellular telephones and oscillate a 'mere' six billion times per second, approximately 100,000 times slower than visible light. The energy of the microwave photons is correspondingly 100,000 times lower and hence these pusillanimous particles are extremely difficult to detect on an individual basis. The electromagnetic energy of a single one of these photons is roughly equivalent in magnitude to the sound energy impinging on your ear if you are standing in Los Angeles and someone in New York drops a pin onto a table.

The Experimental Setup

The Yale experiment is the first to coherently couple a single microwave photon to a single superconducting qubit (quantum bit or artificial 'atom'). There are two key features that made the Yale experiment possible. First, we used an especially designed and microfabricated superconducting electrical circuit as a quasi-one-dimensional resonator (cavity) whose volume is more than one million times smaller than the typical three-dimensional cavities used in the corresponding atomic physics experiments. This confines the feeble energy of the photon to an extremely small space so that the photon will collide very frequently with the artificial atom (superconducting qubit) placed inside the cavity. Second, the artificial 'atom' or qubit is much larger than a single real atom so that, crudely speaking, it represents a bigger target for the microwave photon to hit. The qubit consists of two small pieces of aluminum separated by a thin barrier (Josephson tunnel junction). The qubit is about 1 micrometer in size and even though it contains roughly 1 billion aluminum atoms, the special quantum coherence properties of the superconducting state allow the electrons to travel in pairs (Cooper pairs) and behave

collectively in such a way that the qubit has very simple quantum energy levels, similar to those of an ordinary atom, but on a much lower energy scale matched to the microwaves. The two lowest energy states of the qubit differ by the transfer of a single pair of electrons between the two aluminum grains. More precisely, the energy states of the qubit are coherent quantum superpositions of these two charge states formed as the Cooper pair(s) quantum mechanically tunnel back and forth through the barrier separating the two aluminum grains. The effective size (radius) of this artificial atom is roughly one micrometer, some 10,000 times larger than an individual aluminum atom. This combination of large artificial 'atom' size and exceptionally small cavity volume means that the photon collides with the 'atom' very frequently, some 12 million times per second. Another major advantage of the artificial atom is that it is permanently mounted on the micro-chip exactly at the optimal location to couple to the photon and it cannot escape from the cavity, a nagging problem that atomic physicists routinely face.

When the qubit is absent from the cavity, microwaves are readily transmitted through the cavity at (only) one sharply defined frequency (the cavity resonance frequency) and detected by a sensitive ultra-low noise radio receiver similar to those used by radio astronomers to detect weak signals from distant galaxies. [The microwaves are not detected as individual photons; it takes about 30 photons to obtain a measurable signal, but this is not a serious limitation in the present experiment.] When the qubit is present in the cavity and its excitation energy is tuned to match the resonance frequency of the microwave cavity (something that can be conveniently done with small voltages and magnetic fields applied to the qubit), the cavity ceases to transmit at the original frequency. Because of the strong coupling between the photon and the qubit they form a kind of 'molecule' with two new energy levels (familiar to chemists as bonding and anti-bonding orbitals). If microwaves matched to one of these two new excitation energies are incident on the cavity, they are transmitted through to the detector. Hence one sees peaks in the transmitted power at two different frequencies split apart by 12 MHz (12 million cycles per second, the same frequency mentioned above which is the rate at which the photon and qubit are colliding with each other).

In order to see these peaks (known in atomic physics as vacuum Rabi peaks after I.I Rabi), one must be sure to not allow more than one photon at a time into the cavity. When the input microwave power is a miniscule 10^{-17} watts, there is on average one photon in the cavity. The experiment was done by turning down the power another factor of 5 to 10 so that there would be very little chance of two photons entering the cavity together. [The photons that enter the cavity stay inside only about one microsecond. Hence at the lowest drive power there is still one photon passing through the cavity about every 10 microseconds which is often enough to register a significant signal in the low-noise amplifier, even though it cannot detect the photons individually.]

It is not enough however to merely attenuate the microwaves intentionally being sent into the cavity. One has to take care to cool the cavity and the wires leading down to it to extremely low temperatures because warm objects emit so-called black-body radiation. The heat you feel on your face from infrared radiation coming from a fireplace is an example of such thermally produced radiation. At room temperature a human being

typically radiates about 100 watts of power, but fortunately absorbs nearly the same amount of radiation emitted by the walls of the room. The coldest parts of space, the inter-galactic vacuum regions, are bathed in blackbody radiation left over from the blazingly high temperatures of the big bang at the beginning of the universe and cooled by the subsequent expansion of the universe to a very low temperature just 2.7 degrees above absolute zero. However the energy of the photons used in the Yale experiment is ten times smaller still and the entire device must be cooled to a temperature nearly 100 times colder than the coldest regions of outer space in order to keep blackbody radiation out. Based on the results of the present experiment we estimate that the average number of thermally produced photons in the cavity is well below 0.1.

Significance of the Experiment

Other solid state analogs of cavity QED (quantum electrodynamics) have been envisaged by many authors in superconducting, semiconducting and even micro-mechanical systems. Our experiments constitute the first experimental realization of these ideas. This new regime of matter light (i.e. microwaves) interaction in a circuit, which we refer to as *circuit quantum electrodynamics*, will open new possibilities to perform quantum optics experiments in solids. This is a completely new regime for studying quantum optics with very different parameter values than typically seen in atomic physics. The ultra-strong nature of the coupling of the microwaves to the artificial atom makes it relatively easy to see non-linear optical effects in which photons interact with each other through the atom. It should also soon allow the construction of relatively simple devices for the production and detection of individual microwave photons with high efficiency. The latter would be the analog of a photomultiplier.

The very strong coupling of the microwaves to the qubit also makes it possible to use probe photons sent through the cavity to quickly and accurately determine whether the artificial atom is in its ground state or excited state without changing that state. This type of ‘quantum non-demolition’ measurement or state read out is highly desirable for purposes of building a quantum computer. Such a device consists of quantum bits that unlike ordinary bits, can be in coherent superpositions of 0 (ground state) and 1 (excited state) at the same time. Remarkably, the uncertainty of which state the qubits are is not a draw back, but actually a resource that would allow quantum computers to exponentially speed up certain types of calculations compared to classical computers.

The team at Yale intends to continue developing and refining their approach and to apply it to multiple qubits in a cavity in an attempt to form the other building blocks needed for a quantum computer namely quantum logic gates. In a quantum gate, two qubits interact with each other and the state of one can undergo a change that depends on the state of the other. If successful, this type of quantum electrical circuit with multiple qubits in a microfabricated cavity might someday form the basis for a powerful architecture for quantum computation.