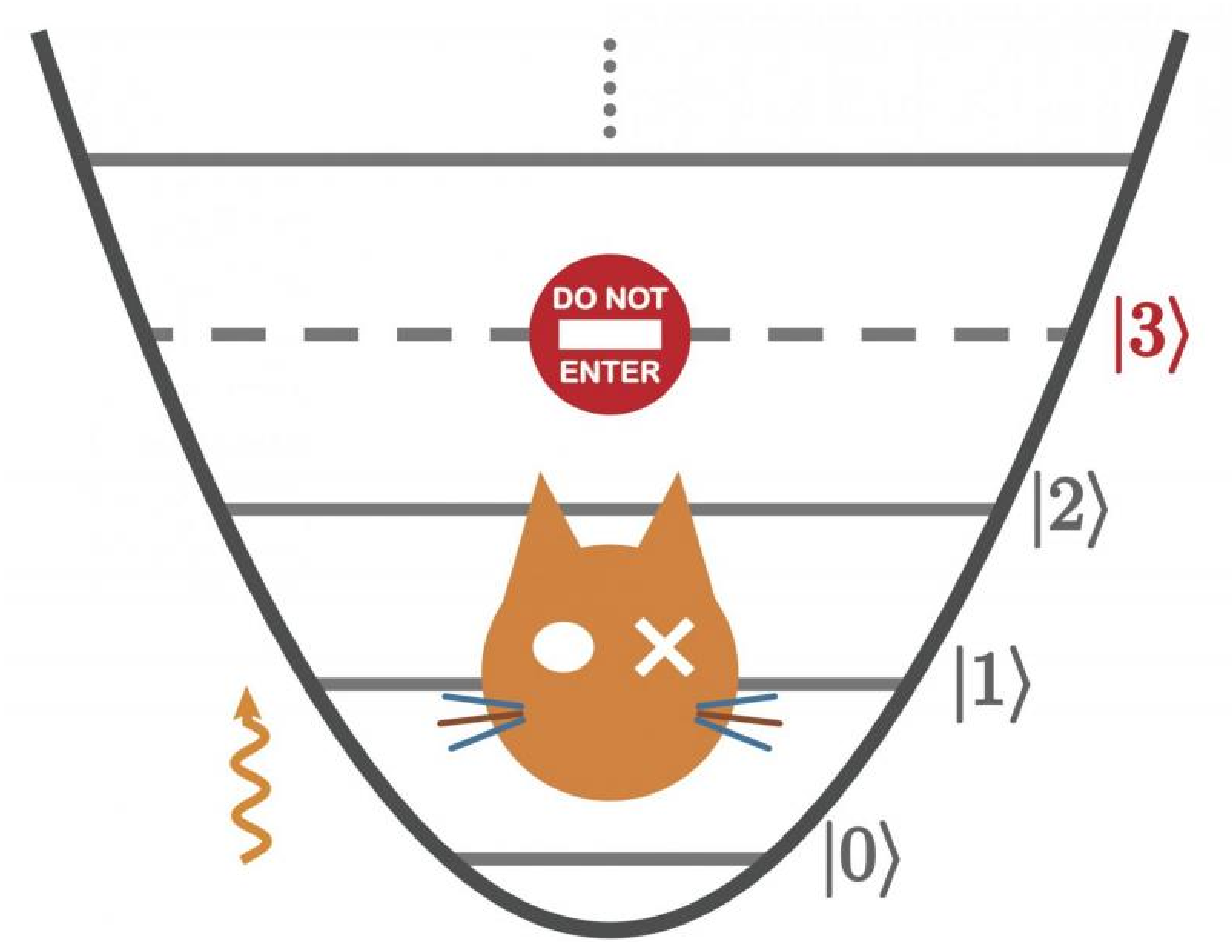
Training Schrodinger's cat: Controlling the quantum properties of light

July 8 2015, by Stuart Mason Dambrot



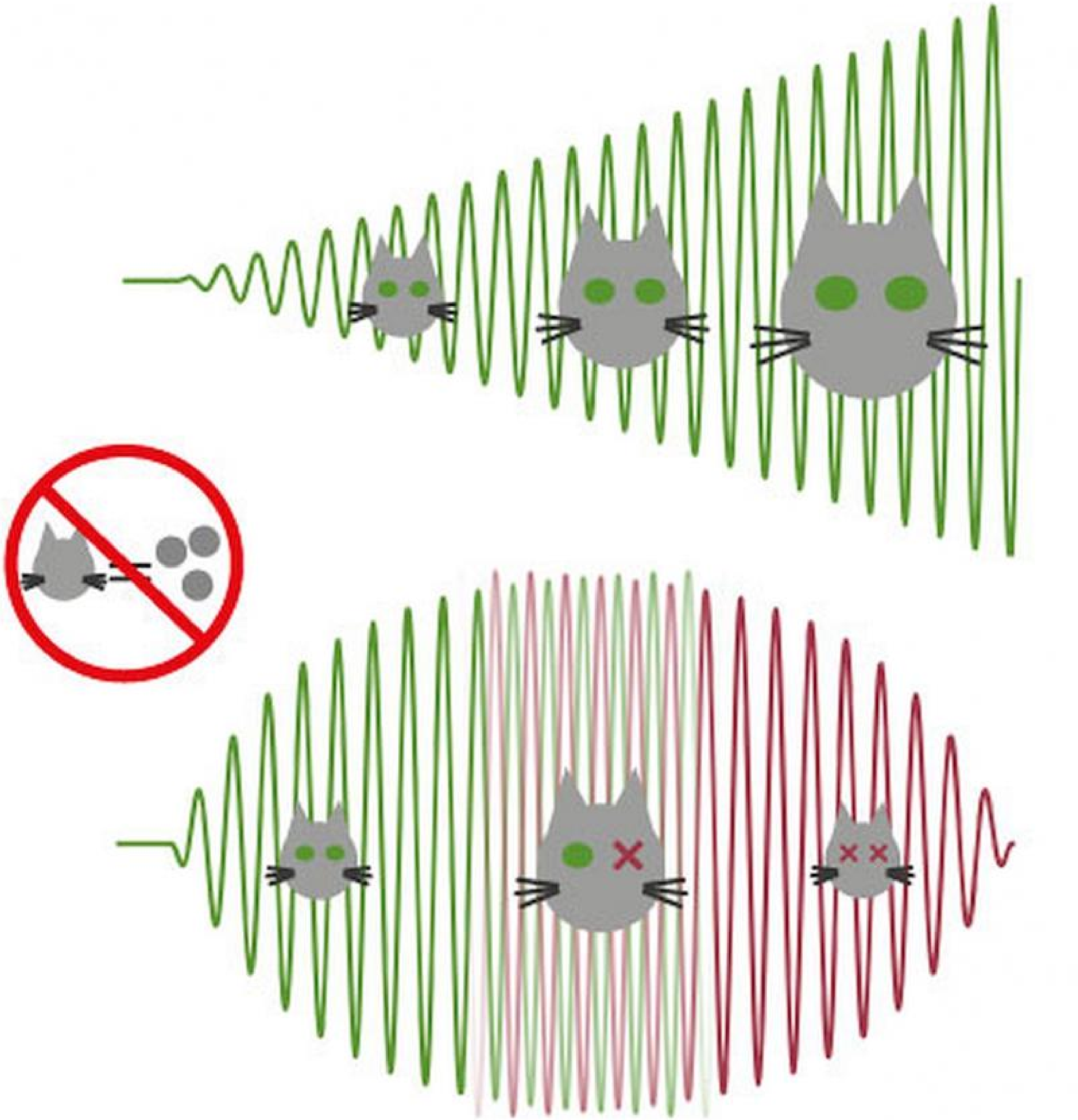
Zeno cat. A Zeno cat refers to non-classical states of light created by shining a cavity on resonance while it is forbidden to access a given energy level. The name originates from the Zeno effect, which can similarly prevent an energy level from being occupied by the sole fact of measuring its occupation frequently. The cat comes from the similarity of such a state with a Schrödinger cat state of light: a superposition between two classical states of light. The Zeno cat figure corresponds to the study's experimental design. Credit: Benjamin Huard.

(Phys.org)—Constructing quantum computers and other quantum devices requires the ability to leverage quantum properties such as superposition and entanglement – but these effects are fragile and therefore hard to maintain. Recently, scientists at Ecole Normale Supérieure in Paris demonstrated a novel method for controlling the quantum properties of light by probing a superconducting circuit in a cavity with microwave photons to control the energy levels that photon quanta can occupy. Specifically, the scientists prevented access to a single energy level corresponding to a number of photons N, and thereby confined the dynamics of the field to levels 0 to N -1. In so doing, the intracavity field changed from a classical wave to a *Schrödinger cat of light* – a superposition between two waves of opposite phases instead of a single one. As a result, this new technique could apply to the development of quantum computers by protecting qubits from decoherence as well as enhancing quantum error correction and quantum systems measurement.

Prof. Benjamin Huard discussed the paper that he and his colleagues published in *Science*. "The primary difficulty in developing our method for manipulating electromagnetic modes by effectively controlling their phase space was to find a proper way of preventing any access to one or few energy levels," Huard tells *Phys.org*. "We did that using another quantum system – a superconducting qubit – which allowed us to change the energy of any level we chose by simply turning a microwave signal on or off. In this context, the main challenge was designing a cavity and a qubit with the right properties to realize and observe this new method of control."

The scientists also had an issue in finding that level occupation oscillated in time when using the same light mode and qubit for several operations. "The basic experiment consists in driving the light mode while the qubit controls its phase space," Huard explains. "However, in order to measure the level occupation in time, we had to use the same qubit as a photocounter, and the same light mode to measure the qubit state." (Photocounters tally photon distributions by counting photoelectric electrons, or photoelectrons – that is, electrons emitted by various metals when illuminated by photons.)

A third obstacle was using circuit quantum electrodynamics, or circuit-QED, architecture – the implementation of quantum electrodynamics (a quantum field theory of electromagnetic force) for circuits – to apply quantum Zeno dynamics (QZD) to light. QZD is based on the quantum Zeno effect (QZE) – named after the Zeno arrow paradox – in which if observed continuously an unstable particle will never decay, meaning that an unstable quantum system measured with sufficient frequency will not evolve. However, in certain circumstances, quantum Zeno dynamics – in which the quantum system changes over time – can occur.



Classical vs. Schrödinger cats. The top figure represents the classical field inside of a cavity which is illuminated by a microwave-generated tone. The phase is well-defined (green corresponds to fields with the original phase, to which a living cat corresponds) and the amplitude increases linearly. The bottom figure represents the experimental results, in which three photons are forbidden in the cavity. In that case, at some time the field amplitude saturates and it enters in a quantum superposition of two possible phases (the original in green and its opposite in red). After this intermediate interval, the amplitude decreases, thereby keeping the opposite phase until it returns to zero amplitude. By analogy, one can say that the intermediate regime corresponds to a superposition of two classical states with opposite phases, very much like a superposition of a dead and living cat. Credit: Benjamin Huard.

"With its large number of energy levels and ease of control," Huard points out, "a single electromagnetic mode offers a wider and more controllable phase space than atoms and two-level systems. Nevertheless, in order to make it work, we had to identify the several constraints on the parameters we had access to. Using superconducting circuits helped since it is fairly easy to tune their parameters and establish coupling to microwave light. Using the same systems twice for various operations required many careful calibrations, and we had to find the optimal temporal sequences to realize the experiment."

Huard addresses the implications of the finding stated in the paper that under a resonant drive, or cavity, the level occupation was found to oscillate in time, similarly to an *N*-level system. "By preventing any access to one energy level of the light mode, it indeed acts exactly as an *N*-level system – but here, since *N* can be chosen and modified in time, it's as if we had engineered an atom with a spin $(N\text{-}1)/2$ that can change at will in time by simply turning on or off microwave signals. It would be interesting to observe the dynamics of such a spin whose number is changing in time."

Huard next discusses how fine control of the field in its phase space may enable applications in quantum information and metrology. "Our method is a new technique that can produce exotic quantum states of light similar to Schrödinger cat states or vacuum squeezed states that are well-suited for quantum information or metrology purposes by increasing the precision of field or position measurements." (A vacuum squeezed state is a nonclassical state of light in which quantum noise is no longer independent of the phase of the light wave, and is below the standard quantum limit.) "Our method can also be used to generate and protect entanglement, which is a fundamental resource of quantum information, as well as to perform quantum error correction on qubits encoded using Schrödinger cat-like states."

In fact, the paper states that the new method allows the possibility of manipulating Schrödinger cat states in a unique way. "Our method is the essential brick that enables the creation of phase space light tweezers, as proposed by Jean-Michel Raimond and coworkers[1]," Huard says. "These tweezers can displace parts of the Wigner function in its phase space one at a time." (The Wigner function is a so-called quasiprobability distribution that links the Schrödinger wavefunction to a probability distribution in phase space, and counterintuitively can have regions of negative probability density.) "It therefore becomes possible to enlarge or rotate a Schrödinger cat state directly in its phase space."

This leads to the ability to effect quantum error correction of cat-qubits (quantum information encoded in logical bases composed of Schrödinger cat states) as a quantum computing paradigm. "In fact," Huard points out, "a way to encode quantum information with superpositions of cat-like states was recently proposed in the context of circuit-QED by Mazyar Mirrahimi and coworkers[2]," adding that finding ways to perform quantum error correction on these states is essential for their potential use in a quantum computing architecture. "We believe that our technique could be used to perform this quantum error correction in a unique way. Indeed, decoherence leads to an exponential relaxation of the cat size, which needs to be overcome – and by displacing the cat 'legs' one by one using QZD, this relaxation can be canceled without losing any quantum information."

Looking ahead, Huard tells *Phys.org* that the researchers are "pursuing the investigation of the fascinating effect of measurement on quantum systems. For instance," he illustrates, "we now have an experiment where we intercept the signal that leaks towards the environment of a qubit and usually leads to decoherence. However, using this signal we can now infer what the environment knows about the qubit state and preserve the purity of the quantum state – and we've recently managed to use that signal for preserving any state by feedback." In addition, he adds, they are interested in applying their technique to systems with longer coherence times and to Schrödinger cat preservations.

Regarding other areas of research that might benefit from their study, Huard concludes that "it's hard to tell right now – but in the long run, if our technique helps build quantum simulators or computers, it could have an impact in many areas requiring intense computation, such as machine learning or chemistry."

More information: Quantum dynamics of an electromagnetic mode that cannot contain *N* photons, *Science* (2015) 348:6236 776-779, doi:10.1126/science.1259345

Related:
[1] Phase space tweezers for tailoring cavity fields by quantum Zeno dynamics, *Physical Review Letters* (2010) 105:213601, doi:10.1103/PhysRevLett.105.213601
[2] Dynamically protected cat-qubits: a new paradigm for universal quantum computation, *New Journal of Physics* (2014) 16:045014, doi:10.1088/1367-2630/16/4/045014

Citation: Training Schrodinger's cat: Controlling the quantum properties of light (2015, July 8)