Researchers demonstrate measurement system able to resolve quantum fluctuations

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In this universe, anything that can vibrate will vibrate, and no oscillator is ever truly at rest.

Even when an object such as an atom or subatomic particle is cooled into its lowest possible energy condition, or "ground state," it still experiences random fluctuations in its position and momentum thanks to the Heisenberg uncertainty principle: The better defined the position is, the more uncertain the momentum, and vice versa.

In short, it's impossible to be motionless. This is not just true on the atomic scale, but also for extremely small, yet still macroscopic objects containing billions of atoms.

These fluctuations are very difficult to detect by conventional means because traditional linear amplification techniques always add some classical noise that can masquerade as "quantum fluctuations." Worse yet, trying to directly measure the energy of these fluctuations is impossible because this so-called "zero-point energy" cannot do any real work – that is, exert a force to move an object—making it in some sense "unreal."

Now Ray Simmonds and colleagues in NIST's Quantum Devices Group have devised and demonstrated a unique measurement system that is able to resolve quantum fluctuations of a tiny aluminum drum that vibrates at shortwave radio frequencies.

The system, which fits on a microchip, comprises three elements: the drumhead mechanical resonator; an attached inductor coil (which, combined with the drum element, functions as a microwave "cavity"–a structure that electrically resonates at about 10 GHz); and an electrically coupled "artificial atom" made from a superconducting Josephson junction (a tiny metal-insulator-metal sandwich).

Previously, the NIST researchers had worked extensively with the drum-and-coil cavity (an "optomechanical" combination) exploring how to cool the mechanical motion to its ground state and how to mechanically store or transfer information. The latest work, reported in *Nature Physics*, adds the artificial atom circuit, providing an ultra-sensitive detector of individual microwave photons trapped inside the electrical cavity.

Using the artificial atom as a new measurement resource, the researchers performed two important, separate tests on the optomechanical system in order to convincingly show the presence of the zero-point fluctuations of the mechanical resonator.

First, they wanted to confirm that the mechanical resonator could be cooled to its ground state by showing that, in this state, it is impossible to remove energy from it. This involves the ability to exchange or "swap" energy back and forth between the mechanical phonons (quantized vibrations) and the photons of microwave light in the cavity. Next, they used a technique known as "parametric amplification" in order to amplify the zero-point fluctuations, which in turn altered the dimensions of the cavity, making the fluctuations "real" and affecting the cavity photons detectable by the artificial atom.

Both the swap and amplification processes are achieved through a coherent pumping of microwave radiation into the inductor coil of the

optomechanical system. (See animation.) These processes originate from the fact that when the mechanical drum vibrates, its motion changes the resonant frequency of the electrical cavity.

Like FM radio, the motion of the drumhead is encoded in the changing frequency of the electrical cavity's tone. Pumping the system at a frequency below the resonance of the cavity by an amount equal to the mechanical vibration frequency produces the swap process, while pumping a mechanical frequency above the cavity resonance provides the amplification process.

Before performing these two experiments, the researchers tested the artificial atom measurement strategy, by creating known amounts of energy within the electrical cavity and reading those out using the artificial atom. This allowed them to characterize not only a coherent input of energy (basic oscillatory motion with a well-defined amplitude and phase) but also a noisy amount of energy –random amplitude and phase, equivalent to thermal heating. That distinction provided a way to differentiate between coherence and random fluctuations.

For each experiment, the researchers began by using the cold electrical cavity (precooled by a liquid helium refrigerator to 25 mK) to cool the mechanical drum's motion to nearly its quantum ground state using previously established techniques. After swapping the mechanical phonons for electrical photons, they used the artificial atom to verify that there was below a single phonon (0.25 on average) in the mechanics.

For the second test, a parametric pump tone is turned on in order to amplify any motion in the mechanical drum. Simmonds described it like this, "The parametric amplification process adds more photons to the cavity and more phonons to the mechanics proportional to how many phonons started in the drum, even if those phonons are coming from noisy quantum fluctuations. After the pump is on for a little while, these

real photons fill the cavity and look like excess heat that can be measured by the artificial atom."

Every amplification process has a "gain" or the multiplicative amount by which the number of photons and phonons is increased from their initial value. The team's Florent Lecocq, who fabricated the chip and performed the experiments, put it this way, "Classically, if nothing is there to begin with, then any number (or gain) times zero is still zero. Even a large gain cannot reveal what's not there. But, due to quantum physics, as Heisenberg realized long ago, this strange, incessant random motion must persist, and this can be amplified."

The researchers determined the gain of their system by amplifying a known amount of coherent motion. After amplifying the system from its ground state, they divide the result by their known gain and thereby reveal that there must have been exactly one quantum of zero-point fluctuations to begin with.

The same system, with modifications, could be used in reverse: The artificial atom could generate specific phonon states on-demand. It could also be employed to explore the quantum dynamics of the mechanical oscillator, or to generate quantum entanglement between phonons and photons.

"Controlling the quantum states of long-lived mechanical oscillators is important for testing these kinds of fundamental, natural properties, like quantum mechanics. A system like this may also become a resource for applications in quantum information," Simmonds says, "and, as demonstrated here, it provides us with a new, powerful, quantum-enhanced platform for developing new detection methods for unbeatable precision measurements."

More information: Resolving the vacuum fluctuations of an

optomechanical system using an artificial atom," F. Lecocq, J. D. Teufel, J. Aumentado & R. W. Simmonds, published on-line in *Nature Physics*. June 15, 2015. DOI: 10.1038/nphys3365

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