Scientists observe a single quantum vibration under ordinary conditions

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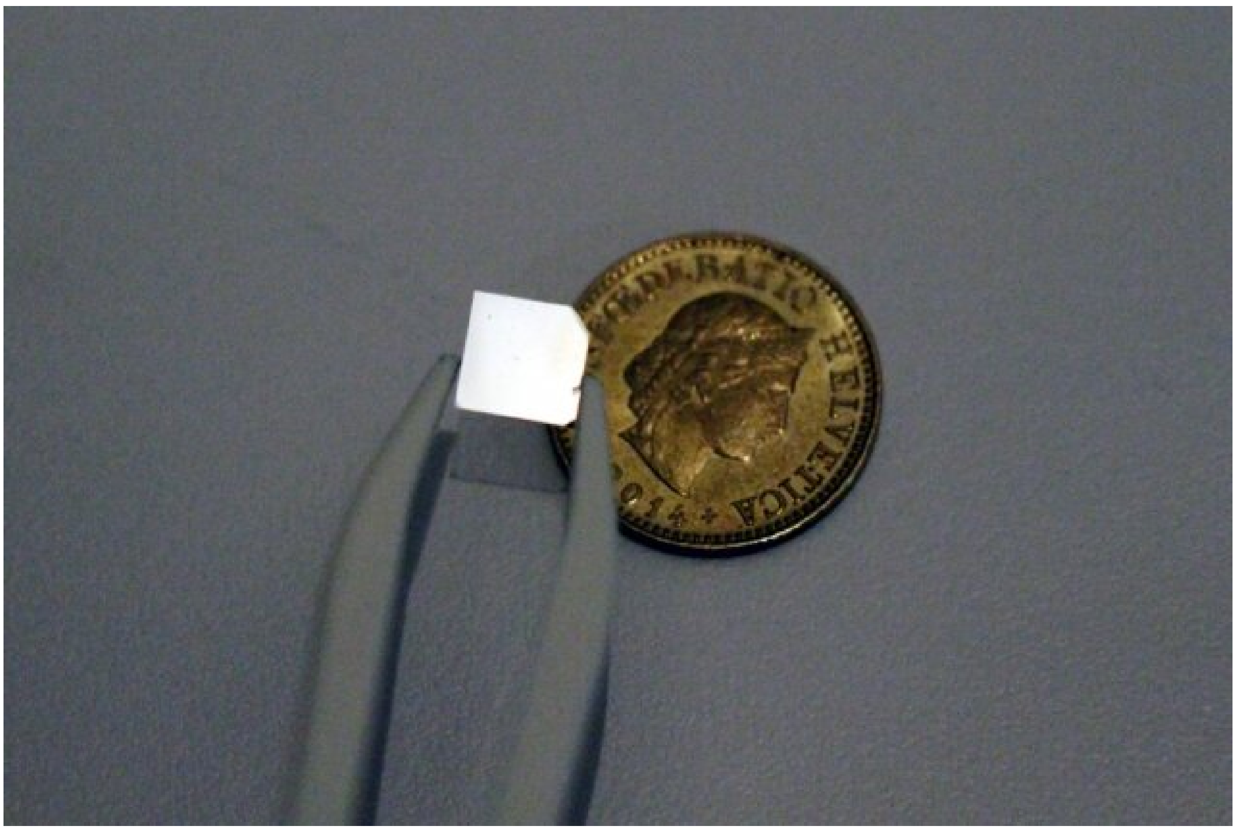

MIT researchers detect a single quantum vibration within a diamond sample (shown here) at room temperature. Credit: Sabine Galland

When a guitar string is plucked, it vibrates as any vibrating object would, rising and falling like a wave, as the laws of classical physics predict. But under the laws of quantum mechanics, which describe the way physics works at the atomic scale, vibrations should behave not only as waves, but also as particles. The same guitar string, when observed at a quantum level, should vibrate as individual units of energy known as phonons.

Now scientists at MIT and the Swiss Federal Institute of Technology have for the first time created and observed a single phonon in a common material at room temperature.

Until now, single phonons have only been observed at ultracold temperatures and in precisely engineered, microscopic materials that researchers must probe in a vacuum. In contrast, the team has created and observed single phonons in a piece of diamond sitting in open air at room temperature. The results, the researchers write in a paper published today in *Physical Review X*, "bring quantum behavior closer to our daily life."

"There is a dichotomy between our daily experience of what a vibration is—a wave—and what quantum mechanics tells us it must be—a particle," says Vivishek Sudhir, a postdoc in MIT's Kavli Institute for Astrophysics and Space Research. "Our experiment, because it is conducted at very tangible conditions, breaks this tension between our daily experience and what physics tells us must be the case."

The technique the team developed can now be used to probe other common materials for quantum vibrations. This may help researchers characterize the atomic processes in solar cells, as well as identify why certain materials are superconducting at high temperatures. From an engineering perspective, the team's technique can be used to identify common phonon-carrying materials that may make ideal interconnects, or transmission lines, between the quantum computers of the future.

"What our work means is that we now have access to a much wider palette of systems to choose from," says Sudhir, one of the paper's lead authors.

Sudhir's co-authors are Santiago Tarrago Velez, Kilian Seibold, Nils Kipfer, Mitchell Anderson, and Christophe Galland, of the Swiss Federal Institute of Technology.

"Democratizing quantum mechanics"

Phonons, the individual particles of vibration described by quantum mechanics, are also associated with heat. For instance, when a crystal, made from orderly lattices of interconnected atoms, is heated at one end, quantum mechanics predicts that heat travels through the crystal in the form of phonons, or individual vibrations of the bonds between molecules.

Single phonons have been extremely difficult to detect, mainly because of their sensitivity to heat. Phonons are susceptible to any thermal energy that is greater than their own. If phonons are inherently low in energy, then exposure to higher thermal energies could trigger a material's phonons to excite en masse, making detection of a single photon a needle-in-a-haystack endeavor.

The first efforts to observe single phonons did so with materials specially engineered to harbor very few phonons, at relatively high energies. These researchers then submerged the materials in near-absolute-zero refrigerators Sudhir describes as "brutally, aggressively cold," to ensure that the surrounding thermal energy was lower than the energy of the phonons in the material.

"If that's the case, then the [phonon] vibration cannot borrow energy from the thermal environment to excite more than one phonon," Sudhir explains.

The researchers then shot a pulse of photons (particles of light) into the material, hoping that one photon would interact with a single phonon. When that happens, the photon, in a process known as Raman scattering, should reflect back out at a different energy imparted to it by the interacting phonon. In this way, researchers were able to detect single phonons, though at ultracold temperatures, and in carefully engineered materials.

"What we've done here is to ask the question, how do you get rid of this complicated environment you've created around this object, and bring this quantum effect to our setting, to see it in more common materials," Sudhir says. "It's like democratizing quantum mechanics in some sense."

One in a million

For the new study, the team looked to diamond as a test subject. In diamond, phonons naturally operate at high frequencies, of tens of terahertz—so high that, at room temperature, the energy of a single phonon is higher than the surrounding thermal energy.

"When this crystal of diamond sits at room temperature, phonon motion does not even exist, because there's no energy at room temperature to excite anything," Sudhir says.

Within this vibrationally quiet mix of phonons, the researchers aimed to excite just a single phonon. They sent high-frequency laser pulses, consisting of 100 million photons each, into the diamond—a crystal made up of carbon atoms—on the off chance that one of them would interact and reflect off a phonon. The team would then measure the decreased frequency of the photon involved in the collision—confirmation that it had indeed hit upon a phonon, though this operation wouldn't be able to discern whether one or more phonons were excited in the process.

To decipher the number of phonons excited, the researchers sent a second laser pulse into the diamond, as the phonon's energy gradually decayed. For each phonon excited by the first pulse, this second pulse can de-excite it, taking away that energy in the form of a new, higher-energy photon. If only one phonon was initially excited, then one new, higher-frequency photon should be created.

To confirm this, the researchers placed a semitransparent glass through which this new, higher-frequency photon would exit the diamond, along with two detectors on either side of the glass. Photons do not split, so if multiple phonons were excited then de-excited, the resulting photons should pass through the glass and scatter randomly into both detectors. If just one detector "clicks," indicating the detection of a single photon, the team can be sure that that photon interacted with a single phonon.

"It's a clever trick we play to make sure we are observing just one phonon," Sudhir says.

The probability of a photon interacting with a phonon is about one in 10 billion. In their experiments, the researchers blasted the diamond with 80 million pulses per second—what Sudhir describes as a "train of millions of billions of photons" over several hours, in order to detect about 1 million photon-phonon interactions. In the end, they found, with statistical significance, that they were able to create and detect a single quantum of vibration.

"This is sort of an ambitious claim, and we have to be careful the science is rigorously done, with no room for reasonable doubt," Sudhir says.

When sending in their second laser pulse to verify that single phonons were indeed being created, the researchers delayed this pulse, sending in into the diamond as the excited phonon was beginning to ebb in energy. In this way, they were able to glean the manner in which the phonon itself decayed.

"So, not only are we able to probe the birth of a single phonon, but also we're able to probe its death," Sudhir says. "Now we can say, 'go use this technique to study how long it takes for a single phonon to die out in your material of choice.' That number is very useful. If the time it takes to die is very long, then that material can support coherent phonons. If that's the case, you can do interesting things with it, like thermal transport in solar cells, and interconnects between quantum computers."

More information: Santiago Tarrago Velez et al, Preparation and Decay of a Single Quantum of Vibration at Ambient Conditions, *Physical Review X* (2019). DOI: 10.1103/PhysRevX.9.041007 , dx.doi.org/10.1103/PhysRevX.9.041007