

physics lurks in living matter (see the article by Paul Davies, *PHYSICS TODAY*, August 2020, page 34).

“But fewer and fewer people remember how to do these calculations,” says Cavagna. The sophisticated math of the RG builds on the methods of quantum field theory, which is increasingly seen as a merely optional part of the physics curriculum, especially for would-be

biophysicists. “Biophysics is so rich in amazing and fascinating problems,” says Cavagna. “But we have so many students coming to us wanting to study the birds, and we have to tell them that they can’t because they don’t know field theory. And you really have to learn it when you’re young—trying to pick it up when you’re 35 or 40 is too late.”

Johanna Miller

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Macroscopic mechanical oscillator is herded into a Schrödinger cat state

A new demonstration of a famous thought experiment has coaxed a classical $16\ \mu\text{g}$ cluster of atoms to behave like a quantum object.

Cats and other everyday things we see don’t appear to exist in two mutually exclusive states at the same time. But Erwin Schrödinger’s thought experiment in 1935—that a cat could be dead and alive simultaneously—and subsequent quantum theory specify that a superposition of two states should be observable even for macroscopic objects. But despite its superlative predictions of phenomena at the smallest scale of matter, large objects don’t appear to exhibit quantum behavior. Does that mean the theory breaks down at some microscopic-macroscopic transition, beyond which quantum mechanics ceases to apply? (For more on the classical-quantum boundary, see *PHYSICS TODAY*, May 2004, page 25.)

One way to test whether quantum mechanics is valid at macroscopic scales is to experimentally generate a cat state, named after Schrödinger’s thought experiment. It’s a quantum state that is a superposition of two classically distinct states at the same time. In phase space, the two states correspond to well-separated probability distributions.

When it comes to determining what counts as macroscopic, researchers don’t entirely agree on a formal definition. But there are two generally accepted criteria that most would say qualify a cat state as macroscopic: The system being studied should be large—often, although not exclusively, measured by its number of atoms—and the two superposed states

should have a distinguishable difference, such as being dead and alive or being separated by a long distance.

Various explanations have been put forth for why macroscopic cat states have never been observed. Perhaps macroscopic objects interact with their environments in such complex ways that no quantum state can survive for any measurable coherence time (see the article by Wojciech Zurek, *PHYSICS TODAY*, October 2014, page 44). Or such objects may have intrinsic sources of noise that interfere with the generation of quantum states.

Nevertheless, numerous experiments have demonstrated Schrödinger cat states at sizes that are approaching macroscopic scales, in trapped-ion quantum computers, superconducting quantum interference devices, Bose-Einstein condensates, and matter-wave interferome-

ters. Now Marius Bild, Matteo Fadel, Yu Yang, and colleagues—all part of ETH Zürich’s Hybrid Quantum Systems Group, led by Yiwen Chu—have created a cat state in a mechanical resonator made of 10^{17} atoms, which is the most massive demonstration to date.¹

Classical-quantum hybrid

The challenges of making cat states are similar to the difficulties that any researcher encounters when studying a system’s quantum behavior. The choice of how much to isolate a quantum system from the environment must be balanced against the efforts to measure it. If a quantum system were completely isolated from its surroundings, no environmental noise would disturb it, and its state would never be measurable. Although cat states and other quantum systems can be well

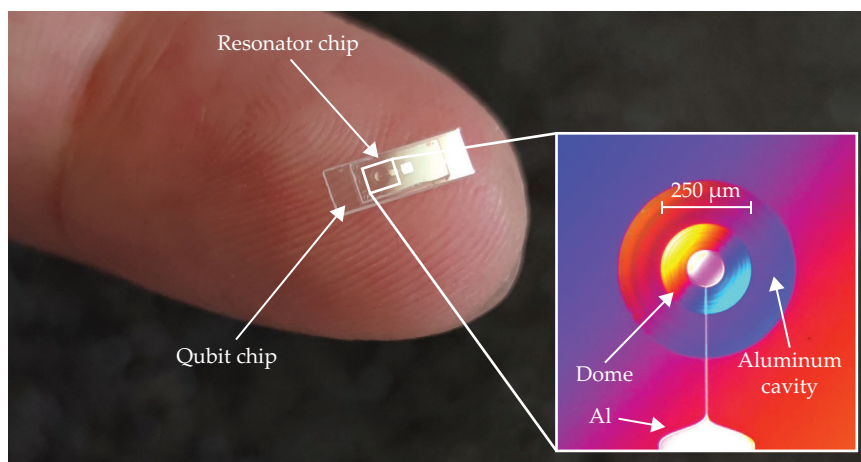


FIGURE 1. A HYBRID QUANTUM DEVICE is made of a superconducting qubit coupled with a classical mechanical resonator, each fabricated onto a sapphire crystal chip. The optical microscopy image (inset) shows a dome of piezoelectric aluminum nitride that strongly couples the two parts of the device, which are placed within a superconducting aluminum cavity. The device generated a Schrödinger cat state—a quantum superposition of, in this case, 10^{17} atoms in the resonator wiggling in two opposite directions simultaneously. (Courtesy of Matteo Fadel.)

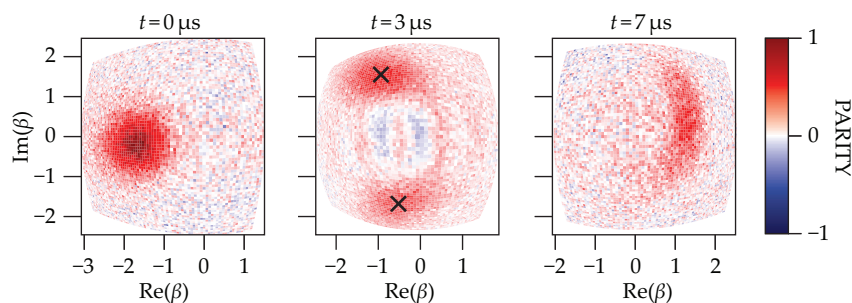


FIGURE 2. WIGNER-FUNCTION MEASUREMENTS show the quantum behavior in a phonon state created in a mechanical resonator coupled to a superconducting qubit. The real and imaginary parts of the complex displacement amplitude β are measured in parity units. The left and right panels show the quantum system immediately before and after the formation of the Schrödinger cat state, shown in the middle panel. It's characterized as a superposition of oscillations from the resonator that have displacements in opposite directions. The two components of the cat state (black crosses) have interference fringes in between, which indicates that the two are in a coherent quantum superposition. (Adapted from ref. 1.)

isolated, the size of macroscopic ones makes them particularly sensitive to noise.

To balance those issues, Chu and her colleagues have been working over the past several years on developing hybrid quantum systems that couple a classical solid-state material to a quantum device.² That approach allows not only for the system to be relatively large but also for the quantum half of it to be well controlled and isolated. Rather than focus on inducing quantum behavior in light, atoms, or other commonly studied platforms, the group at ETH Zürich has been designing an acoustodynamical system.

One part of the device is a superconducting transmon qubit. It's a type of two-state quantum system with a well-defined charge—in this case, from Cooper pairs of superconducting electrons.³ Transmons, and superconducting qubits in general, are less sensitive to noise than some other qubits and are relatively easy to control and measure (see *PHYSICS TODAY*, July 2009, page 14).

The classical half of the hybrid quantum system is an acoustic-wave resonator fabricated on a sapphire crystal. Coupling the resonator to the superconducting qubit is a dome of piezoelectric aluminum nitride, which converts the qubit's electrical signal into quantum mechanical oscillations of the resonator. The dome needs to strongly couple the qubit to the mechanical mode, but at the same time, it must also confine the mechanical oscillations in a well-defined volume so they can be measured.

The cat state is created when sound waves generated by the piezoelectric material interact with the qubit and induce a superposition of two opposite-phase oscillations of atoms in the crystal lattice. Those

oscillations are phonon modes—collective excitations of all the atoms that can be thought of as quantized sound waves. The entire apparatus, shown on a finger in the photo in figure 1, sits in an aluminum cavity that isolates the qubit from environmental noise.

Cat out of the bag

In classical mechanics, a particle can be represented by a point in phase space with a definite position and momentum. But because of the Heisenberg uncertainty principle, that approach doesn't work for quantum phenomena. Instead, a quantum state can be represented by a quasi-probability distribution in phase space, called a Wigner function, that gives a description of the system's state.

To confirm the existence of the cat state, Chu and her colleagues measured the Wigner function of the phonon state. Unlike classical probability distributions, it can take on positive and negative values. Because negative values of the Wigner function have no classical interpretation, seeing them means that the system has an intrinsic quantum mechanical nature rather than some sort of statistical mixture, such as having a cat be dead 50% of the time and alive for the other 50%.

The researchers first allowed the resonator and qubit to interact and become entangled, and the left panel of figure 2 shows the measured Wigner function for the initial phonon state. After about 3 μ s, the cat state emerged in the coupled qubit-resonator system. As shown in the middle panel, the cat state is characterized by two distinct components with interference fringes between them—the telltale sign that the two components are in a coherent quantum superposition.

The excitation in the mechanical resonator lasted for as long as 80 μ s and consisted of atoms in the resonator's crystal lattice wiggling in two directions with opposite displacement amplitudes of about 2.1×10^{-18} m, which is a fraction of a proton's radius.

Although that subnuclear distance is much shorter than in other demonstrations of cat states,⁴ Chu and her colleagues are just getting started, and they expect to see mechanical cat states with larger amplitudes in the future. Markus Arndt of the University of Vienna says that “the system of circuit quantum acoustodynamics is pretty unconventional. I had not expected to see a Schrödinger cat realized in such a system, and I admire what they have achieved.”

Sound bytes

Seeing if it's possible to generate macroscopic cat states is good for more than testing how quantum mechanics works at large scales. Such states are also useful for various quantum technologies, including error-protected processing of quantum information.

Mechanical resonators have greater storage capacity compared with electromagnetic resonators and other quantum-information storage devices. Because the speed of sound is slower than the speed of light, a mechanical resonator has more motional degrees of freedom that are available for storing quantum information, per unit volume. That advantage, however, is limited for now at least because of the coherence time. In the mechanical system by Chu and her colleagues, the coherence time is about an order of magnitude less than competing microwave-cavity technology.

But Chu and her colleagues think they're capable of closing that gap. “I definitely don't think we've hit the upper limit,” says Chu. “People have made better qubits and better resonators. I think for us, the challenge is to maintain those properties, make improvements, and then maintain them once we put everything together.”

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