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QUANTUM COMPUTING

The journey to a mechanical qubit

An acoustic resonator can be directly manipulated to store quantum information

By *Fabio Pistolesi*

Quantum computing can handle complex calculations that are otherwise infeasible for classical computers, which use binary logic (a bit, or digital information, is a 0 or 1). However, a quantum bit (qubit) often has a short lifespan, or coherence time, which is not sufficient to process a multitude of problems. Mechanical systems such as resonators can give long lifetimes compared to quantum systems that are used for qubits. Resonators change shape in response to perturbations and can be coupled with a variety of external signals to create devices such as sensors and transducers, but at the quantum level their direct manipulation is challenging. On page XXX of this issue, Yang *et al.* (1) report a bulk acoustic resonator coupled with a superconducting qubit that can be directly manipulated. This allows a mechanical resonator to store quantum information.

A common example of mechanical systems is a macroscopic transducer, such as a speaker, which converts electrical signals into sound waves. Decreasing their size to the nanometer scale has enabled resonance at high oscillation frequencies and thus, entry into the quantum regime (non-classical state) at cryogenic temperatures. In a quantum system, an atom or a subatomic particle can exist simultaneously in multiple states. This phenomenon, known as quantum superposition, serves as the essence of a qubit that is the building block of quantum computation. A qubit, which is a basic unit of quantum information, is a system formed by the superposition of two distinct energy states. A standard approach to control a qubit is to drive a quantum system with an oscillating external field, such as an electromagnetic wave. When the applied field's frequency (times the Planck's constant) matches the difference between two energy states, called energy spacing, the probability of observing the system in each of the two states cycles between zero and one. This phenomenon, called the Rabi oscillation, allows controlled transitions between the two quantum energy states.

For this control method to work, only two states must be resonant with the external field. For example, an atom has uneven energy

spacings between its electronic energy states. Thus, the frequency of an external light (electromagnetic wave) can be matched to the difference between two specific energy states in order to achieve Rabi oscillations. In contrast, a mechanical resonator operating at the small oscillation amplitudes typical of the quantum regime, demonstrates ideal harmonic behavior—the oscillation frequency is proportional to the energy difference between two states and independent of the amplitude (the energy of the state). The energy states are evenly spaced, which makes the frequency-based selection of two specific states impossible (see the figure).

To overcome the harmonicity of a mechanical oscillator, Yang *et al.* coupled a bulk mechanical resonator to a superconducting qubit. The electric field of the superconducting qubit induces the deformation of a small piezoelectrical crystal that can convert electrical signal to mechanical deformation, and vice versa. This creates an effective mechanical anharmonicity and enables control of two specific energy states of the resonator by an electromagnetic wave. Earlier studies manipulated the quantum states of a piezoelectrical mechanical harmonic resonator by transferring a quantum of energy (the smallest discrete unit of energy) between the superconducting qubit and the resonator (2). This energy transfer occurs when the superconducting qubit's frequency is in resonance with that of the oscillator, allowing Rabi oscillations between the two systems. Various mechanical resonators implemented with surface acoustic waves (3, 4), a suspended drum (5), and suspended nanomechanical beams (6, 7) have been manipulated with a superconducting qubit. Likewise, this has led to achieving coherent quantum state transfers between two qubits (8), a single mechanical state control (9), and high-fidelity control of quantum states (10). However, previous work required transferring energy (or quantum information) between the qubit and the resonator rather than making a mechanical resonator itself as a qubit.

Recent studies suggested that leveraging the strong coupling between the flexural mechanical mode of a suspended carbon nanotube (like a guitar string) and an electronic qubit embedded in the nanotube can create large mechanical anharmonicity for quantum manipulation of the resonator (11). Such large

anharmonicities have been also experimentally observed (12). However, quantum operation is currently limited by large decoherence—a process by which qubits lose their quantum state—in the electronic environment. Yang *et al.* implement a similar strategy but chose a mechanical system in the microwave range of electromagnetic waves that is very close to the frequency of the superconducting qubit but off-resonance. This allows to take advantage of the long coherence time of a superconducting qubit and work in the dispersive regime. It produces a shift of the qubit's frequency that depends on the resonator's energy state. When this frequency shift is larger than the decoherence rate (decay rate of a qubit) of both the resonator and the qubit, it allows to detect the energy state of the resonator by measuring the qubit (5, 6, 13). Subsequently, this induces mechanical anharmonicity in the resonator. Yang *et al.* exploited the modifications induced in the transition frequency (energy spacing) between the second and third excited energy states of the mechanical resonator. This allowed the authors to investigate the crossover from a harmonic to a strongly anharmonic resonator when the anharmonicity becomes larger than its decay rate. Additionally, they could demonstrate Rabi oscillations between the lowest two energy states of the selected mode and prepare any desired superposition of the two distinct states for quantum operation.

The results obtained by Yang *et al.* demonstrate that a mechanical resonator can function as a qubit. Exciting perspectives open from this achievement. Given the long coherence times (lifetime of a quantum state) observed in mechanical resonators (10), similar methods could lead to a new class of qubits with extended operation times (11) in which information is stored in the mechanical displacement. Mechanical qubits may also enable quantum force sensing protocols (measuring atomic scale forces) (14) with substantially improved sensitivity. The bulk mechanical resonator in the study of Yang *et al.* and similar systems with large center-of-mass displacement, such as carbon-nanotube resonators, may serve as intriguing testbeds for exploring fundamental limits on coherence of quantum state.

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Making a qubit with a mechanical resonator

A mechanical resonator behaves harmonically in the quantum regime, which has the same spacing between two energy states. This makes it impossible to select two distinct energy states for a qubit. Slight off-tuning of the resonator's energy states by coupling with a superconducting qubit enables selection of two distinct energy states that, when forced by an oscillating field, can oscillate between 0 and 1 to store and deliver quantum information.

