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QUANTUM PHYSICS

A massive squeeze

A Cooper-pair box qubit is used to squeeze the energy of a heavy oscillating membrane towards a quantum energy eigenstate, bringing measurements of how mass and quantum mechanics interplay one step closer.

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Whilst quantum mechanics perfectly describes the physics of small and light objects, there are few experiments exploring its applicability to larger scale systems, in particular where gravity may play a role. Writing in *Nature Physics*, Xizheng Ma and colleagues have now reported a device that can control the quantum state of a massive oscillating membrane, by interfacing the membrane with a qubit. They demonstrated the creation of an energy squeezed state — a state of mechanical motion bearing non-classical features. This new platform presents a new way to explore macroscopic quantum mechanics.

Over a century of experimentation has validated the theory of quantum mechanics, where particles can be entangled despite huge distances between them, or a single object can exist in a superposition of two states. For practical reasons, these experiments have mostly been restricted to very small and light objects. The existence of an upper limit in terms of size and mass, possibly related to the incompatibility of quantum mechanics with general relativity[1], remains to be explored experimentally[2].

One technical reason why large and heavy objects are more difficult to use in quantum experiments is the relation between mass, frequency and temperature. If we consider a harmonic oscillator, lower frequency translates to an enhanced sensitivity to the thermal energy of the environment. The large mass of the membrane used in this experiment causes it to oscillate at 25 MHz. Even at the cryogenic temperatures accessed in work (10 millikelvin), the thermal energy then overwhelms the mechanical energy corresponding to 25 MHz. The membrane's state is scrambled over many quantum energy levels, creating a mixed thermal state (Fig. 1 (b)). Another issue is the harmonic nature of the oscillating membrane motion, which gives rise to a 'ladder' of quantum states separated by the same energy (Fig. 1 (b,c)). Because of this equal spacing, the quantum states cannot be discriminated by a classical oscillating force, which can only access the level differences.

[1] Penrose, R. (1996). On gravity's role in quantum state reduction. General relativity and gravitation, 28(5), 581-600.
[2] Bassi, A., Lochan, K., Satin, S., Singh, T. P., & Ulbricht, H. (2013). Models of wave-function collapse, underlying theories, and experimental tests. Reviews of Modern Physics, 85(2), 471.

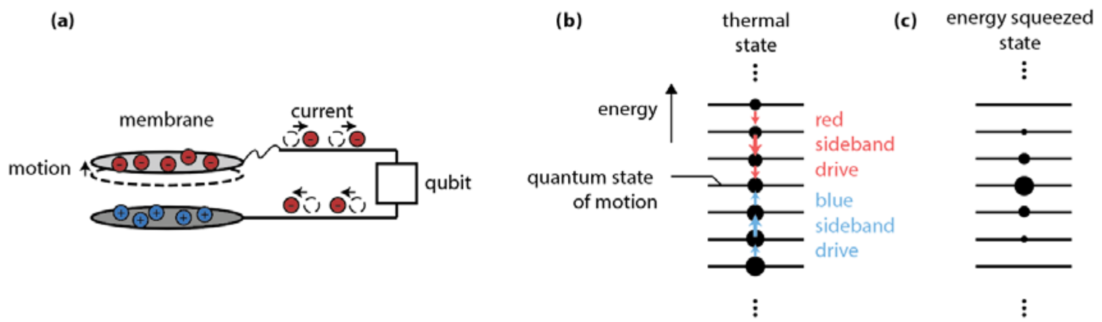

Figure 1 | Controlling the quantum state of a massive membrane. (a) Ma and colleagues report a way to control the quantum state of a massive oscillating membrane, by interfacing it with a qubit. Enabling this is a "Cooper-pair box" qubit which is very sensitive to the charge oscillations created by the moving charged membrane. **(b)** The qubit allows access to the quantum states of motion through sideband drives. Red and blue sideband drives are used to bring a portion of quantum states to a lower or higher energy, respectively. The probability of a state being occupied is represented by the size of the black circle. **(c)** The resulting energy squeezed state is close to a pure quantum state of motion and is inherently non-classical.

Ma and colleagues addressed the issues of temperature and harmonicity by coupling the membrane to a qubit (Fig. 1 (a)). The qubit was built out of superconducting circuitry, which is a leading technology for the development of a quantum computer[3]. The authors, did, however, use a rather dated circuit — the 'Cooper-pair box' qubit — which has now been discarded by quantum computing research, as it is overly sensitive to charge fluctuations in its environment[4]. But this bug was actually a feature in this experiment, because it is precisely this sensitivity that enabled a high coupling strength between the qubit and the membrane. Indeed, the membrane was charged with a DC voltage in such a way that, when it moved, it created a current that was picked up by the qubit. Each state of the membrane led to a different current, which shifted the frequency of the qubit. So, measuring the qubit frequency yielded information about the quantum state of the membrane[5].

The team exploited this coupling to create non-Gaussian (i.e. quantum) states of motion, making this one of the few, very recent, experiments to demonstrate control over the quantum state of such a massive, low-frequency mechanical oscillator [6] [7]. To do so, they used sideband drives — microwave radiation at specific frequencies — which allowed the exchange of excitations between the membrane and the qubit. For example, by driving the system at the difference between the qubit frequency and the membrane's mechanical frequency, they provided exactly the right amount of energy for an excitation in the mechanical oscillator to become an excitation in the qubit. Because qubit excitations are rapidly dissipated, this sideband drive effectively lowered the energy level occupied by the mechanical oscillator, moving the quantum state of the membrane down its ladder of excitations (Fig. 1 (b)). This is typically referred to as a 'red' sideband — because it has a lower

[3] Arute, Frank, et al. "Quantum supremacy using a programmable superconducting processor." Nature 574.7779 (2019): 505-510.
[4] Koch, Jens, et al. "Charge-insensitive qubit design derived from the Cooper pair box." Physical Review A 76.4 (2007): 042319.
[5] Viennot, J. J., Ma, X., & Lehnert, K. W. (2018). Phonon-number-sensitive electromechanics. Physical review letters, 121(18), 183601.
[6] Reed, A. P., et al. "Faithful conversion of propagating quantum information to mechanical motion." Nature Physics 13.12 (2017): 1163-1167.
[7] Ockeloen-Korppi, C. F., et al. "Stabilized entanglement of massive mechanical oscillators." Nature 556.7702 (2018): 478-482.

frequency than the qubit — and can be used to move all the way down the ladder of excitations to reach the ground-state of mechanical motion[8]. In a similar process, a ’blue’ sideband— driven at a higher frequency than the qubit —will move the state up the ladder of excitations (Fig. 1 (b))

The originality of this device is that the qubit’s frequency depends on the state of the mechanical oscillator. In turn, the qubit’s frequency determines the frequency of a sideband, and the sideband can therefore target a specific group of states on the ladder of mechanical excitations. As illustrated in Fig. 1 (b), by driving both red and blue sidebands the system approaches a pure quantum state (Fig. 1 (c)) in a process called energy squeezing.

Increasing the coupling between the qubit and the membrane to the so-called phonon-number-resolving regime would allow individual states rather than groups of states to be addressed. Energy squeezing would then result in a pure quantum state, which could kick off exciting experiments to test the macroscopic limits of quantum mechanics.

[8] Teufel, John D., et al. "Sideband cooling of micromechanical motion to the quantum ground state." Nature 475.7356 (2011): 359-363.