A macroscopic oscillator goes and stays quantum

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A milestone for the coherence time of a macroscopic mechanical oscillator may be a crucial advance for enabling the development of quantum technologies based on optomechanical architectures and for fundamental tests of quantum mechanics.

Mechanical oscillators in the quantum regime are enormously versatile. Their high sensitivity and ability to couple to electromagnetic fields of different frequencies make them valuable building blocks for (future) quantum applications, for example as transducers connecting hybrid components or in precision measurements of small forces, displacements and masses. However, such optomechanical architectures are coupled to the environment and thus exposed to decoherence, which limits their usability. Now, as they report in *Nature Physics*, Amir Youssefi and co-workers have realized an optomechanical circuit with an ultralow thermalization rate[1], enabling high-fidelity ground- and squeezed-state preparation of a mechanical oscillator.

The control, read-out and manipulation of motional degrees of freedom via electromagnetic radiation lie at the heart of cavity optomechanics[2]. Although the basic principles of radiation pressure forces — the force photons exert on matter — have been well known since Johannes Kepler's initial studies of comets in the seventeenth century, the field has expanded tremendously over the past few decades. Besides being promising candidates for technological applications, optomechanical systems allow fundamental tests of quantum mechanics, such as entanglement with macroscopic objects or the study of the classical-to-quantum transition.

There are many different designs of optomechanical devices, ranging from the atomic scale to macroscopic mirrors used for gravitational wave detection[3], but microwave circuits coupled to mechanical resonators are a particularly successful platform. So-called circuit optomechanics consists of a capacitor with one moving plate, the drumhead resonator, embedded in a superconducting circuit, which serves as a cavity for the electromagnetic field. This architecture has allowed the cooling of a mechanical mode to its quantum ground state[4], the preparation of a mechanical squeezed state[5] and the entanglement of two mechanical oscillators[6].

Like all quantum architectures, optomechanical systems face the challenge of undesired coupling to environmental degrees of freedom, which leads to loss of energy and information. These decoherence processes are characterized by the thermalization and dephasing rate. Decoherence limits the performance of mechanical oscillators in precision metrology, as well as quantum memories, and, crucially, makes the preparation of non-classical states of the mechanical system extremely challenging. Recently, impressive progress has been made regarding the thermalization rate in an optomechanical crystal architecture[7]; however, although the mechanical excitation lived for one second, the coherence time, that is, the quantum-state lifetime, only reached a few hundred microseconds.

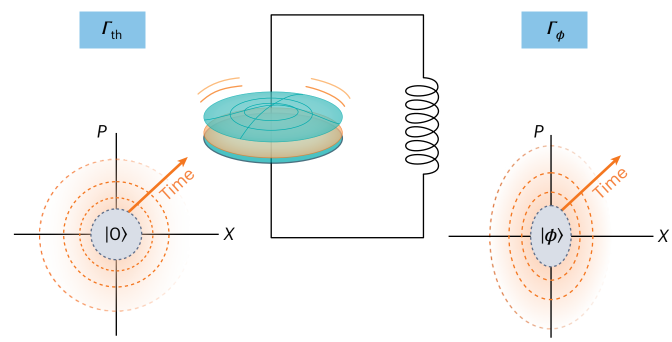

Fig. 1 | Measuring decoherence and dephasing rates. A mechanical mode of a drumhead resonator in an optomechanical circuit is prepared in the ground (|0>) and a squeezed (|ϕ>) state, here represented in the phase space of the X and P quadrature of the mechanical mode. The thermalization out of the ground state gives access to the thermal decoherence rate (Γ_{th}, left), while the dephasing rate is extracted when the system is initialized in a squeezed state (Γ_ϕ right).

Youssefi and co-workers have now demonstrated a quantum-state lifetime on the order of 10 ms, and thus realized a factor of one hundred improvement for the lifetime of the mechanical state compared with previous optomechanical experiments. To achieve this, they developed an aluminium-based superconducting circuit, including a drumhead resonator with an extremely high quality factor. Crucially for achieving the observed long coherence time, the developed circuit architecture also possesses an ultralow dephasing rate. The low-decoherence architecture operates well inside the so-called resolved sideband regime, in which the mechanical frequency exceeds the linewidth of the cavity. This allows for efficient dynamical back-action cooling of the mechanical mode, which involves mechanically assisted scattering of photons from below the cavity frequency to higher frequencies, destroying mechanical excitations and thus cooling the resonator. The team cooled their mechanical oscillator into its ground state with a fidelity of 93%, which corresponds to an average occupation of 0.07 phonons.

To extract the thermal decoherence rate, Youssefi and co-workers prepared the system in its motional ground state and monitored the evolution to the thermal equilibrium state with time (Fig. 1). For short evolution times they observe a 7.7 ms lifetime of the phonon, corresponding to a thermalization rate of 20 Hz, a noticeable advance given that previous optomechanical circuit architectures have rates in the kilohertz regime. Moreover, the team prepared the mechanical mode in a squeezed state[5,8], which is phase-sensitive, and thus thermalization out of this state gives access to the dephasing rate, which was around 90 mHz for the measured system.

The combination of a high quality factor and the ultralow decoherence rate for the mechanical mode have enabled a milestone to be reached regarding the quantum coherence time for an optomechanical system. Moreover, the achieved ultralow dephasing and thermal decoherence rates outperform the quantum-state lifetime in state-of-the-art superconducting qubits. Youssefi and colleagues' work places a rather understudied quality in the focus of optomechanics — the dephasing rate. Although it is crucial for characterizing the quality of a qubit, dephasing in optomechanical architectures has only rarely been reported, most likely because thermal decoherence usually outweighs it.

The team's superconducting-circuit platform has many interesting prospects, as it can be integrated into hybrid architectures with microwave qubits. This is an intriguing perspective. On the one hand, the mechanical mode with its long lifetime could serve as a quantum memory storing quantum information. On the other hand, the coupling to the qubit provides a nonlinearity that can be used to create truly non-classical states in the mechanical mode. Moreover, for the long coherence time Youssefi and co-workers observed, fundamental tests of quantum mechanics with microwave optomechanical circuits come within reach, such as teleportation protocols[9] or Bell tests.

Although low coupling to the environment is necessary for optomechanical quantum applications, another challenge remains: the coupling between single photons and phonons also needs to be large. Using inductive instead of capacative coupling in circuit optomechanics[10] has made progress in this regard, but such circuits are still overwhelmed by thermal decoherence. Realizing strong optomechanical coupling in combination with ultralow thermal decoherence would allow optomechanics to boldly go where no resonator has gone before.

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Competing interests

The author declares no competing interests.