Quantum Ground State and Single Phonon Control of a Mechanical Resonator

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Quantum mechanics provides a highly accurate description of a wide variety of physical systems. However, a demonstration that quantum mechanics applies equally to macroscopic mechanical systems has been a long-standing challenge, hindered by experimentalists' inability to cool a mechanical mode to its quantum ground state. The temperatures required are typically far below those attainable with standard cryogenic methods, so significant effort has been devoted to developing alternative cooling techniques. Once in the ground state, quantum-limited measurements must then be demonstrated. Here, using conventional cryogenic refrigeration, we show that we can demonstrably cool a mechanical mode to its quantum ground state, by using a microwave-frequency "quantum drum" coupled to a quantum bit, a device developed for quantum computation. We further show that we can controllably create single quantum excitations in the resonator, thus taking the first steps to complete quantum control of a mechanical system.

Background

The bizarre, often counter-intuitive predictions of quantum mechanics have been observed in atomic-scale, optical, and electrical systems. Efforts to demonstrate that quantum mechanics also applies to a mechanical system, especially one that can be seen with the naked eye, have generated significant interest[1–13]. Most approaches focus on measuring the behavior of a single mechanical resonance. Cooling a mechanical resonance, also called a mode, to its quantum ground state is typically an enormous challenge, as this requires temperatures $T \ll hf/k_B$, where f is the mode frequency, and h and k_B are Planck's and Boltzmann's constants, respectively. An audio frequency mode at $f = 1$ kHz, for example, would need to be cooled to $T \ll 50$ nK. However, the resonant frequency scales inversely with the size of the system, with higher characteristic frequencies displayed in smaller systems. Researchers have therefore pursued combinations of very small mechanical resonators together with novel cooling techniques[14–18]. The use of nanomechanical resonators, with mode frequencies in the MHz band, eases the stringent temperature requirements, and when combined with quantum optics-based refrigeration, has allowed a number of demonstrations of near-quantum-limited behavior[19–22].

Here, using conventional cryogenic refrigeration, we show that we can demonstrably cool a mechanical mode to its quantum ground state. We achieve this by using a micromechanical resonator[5] with an isolated mechanical mode near 6 GHz, a microwave-frequency "quantum drum," whose ground state is reached for temperatures below ~ 0.1 K, easily achieved using a dilution refrigerator. We perform quantum-limited measurements of the resonator using a superconducting quantum bit (a qubit), an electronic device developed for quantum computation[23,24]. Coupling such a quantum device to the resonator should allow completely quantum-coherent measurements, preserving the quantum states in the coupled system; by contrast, strongly coupling the resonator directly to a classical measurement system typically causes rapid decoherence of these states.

Using the qubit, we measure that the micromechanical resonator has been cooled to its ground state, and estimate that the maximum number of phonons in the relevant mechanical mode is $\langle n \rangle_{\max} < 0.07$, i.e. the resonator is in its ground state with greater than 93% probability. We use our time-domain control of the qubit-resonator interaction to further show that we can controllably create an individual quantum excitation (a phonon) in the resonator, and observe the exchange of this quantized excitation between the resonator and the qubit. We also use a classical excitation to generate a coherent state in the resonator, which yields a qubit response that is in good agreement with theory. This demonstration provides strong evidence that quantum mechanics applies to a mechanical object large enough to be seen with the naked eye.

Mechanical Resonator and Quantum Bit

We have chosen to use a micromechanical bulk dilatational resonator[25,26], with a fundamental dilatational resonance frequency $f_r \sim 6$ GHz. We fabricate the resonator from a piezoelectric material so that the mechanical motion generates electrical signals, and vice versa. This electromechanical coupling allows us to measure the resonator with a quantum electrical circuit, a superconducting phase qubit. Qubits allow straightforward quantum-limited measurements of resonators[27,28], and here allow us to unambiguously demonstrate that the mechanical system can be cooled to its ground state, as well as excited with individual mechanical quanta.

We first developed a method to fabricate the high frequency mechanical resonator. The resonator is a film bulk acoustic resonator (FBAR) [25], comprising a thin film of aluminum nitride, a strong piezoelectric [29], sandwiched between two aluminum metal electrodes. The active part of the structure is mechanically suspended. The resonator responds to voltages by expanding or contracting in the direction perpendicular to the metal electrodes, with a fundamental resonance frequency $f_r = v/2t$, where v is the average sound speed and t the resonator thickness. An electron micrograph of a typical resonator, along with its equivalent electrical circuit and a classical resonance measurement, are shown in Fig. 1. Extensive experiments were made on a variety of mechanical resonators with this design to ensure that the resonance was indeed mechanical in nature; see Supplementary Information.

We co-fabricated the mechanical resonator and superconducting qubit on a single chip by first lithographically defining the mechanical structure and subsequently patterning the qubit. The fabrication process involved 13 layers of lithography, including metal and dielectric deposition and etching steps (see Supplementary Information). In the last step, the device was exposed to xenon difluoride gas to release the mechanical resonator. A photomicrograph of a completed device is shown in Fig. 2.

Our quantum electrical circuit is a Josephson phase qubit [23,24,30], comprising a Josephson junction shunted by a parallel capacitor and inductor. The qubit can be approximated as a two-level quantum system, with a ground state $|g\rangle$ and excited state $|e\rangle$ separated in energy by ΔE, whose transition frequency $f_q = \Delta E/h$ can be set between 5 and 10 GHz. The qubit frequency is precisely controlled by a current bias, which is applied using an external magnetic flux coupled through the parallel inductor. The state of the qubit is measured using a single-shot procedure [23]; accumulating ~ 1000 such measurements allows us to determine the excited state occupation probability P_e (see Supplementary Information). We have previously used the phase qubit to perform one- and two-qubit gate operations [24], to measure and quantum-control photons in an electromagnetic resonator [27,28], and to demonstrate the violation of a Bell inequality [31]. Here, the qubit and mechanical resonator are coupled through an interdigitated capacitor $C_c \approx 0.5$ pF, so as to maximize the coupling strength between the qubit and resonator, while not overloading the qubit. The coupled system can be modeled by the Jaynes-Cummings Hamiltonian [32], allowing us to estimate the coupling energy g between the mechanical resonator and qubit, which involves the coupling capacitance as well as the electrical and mechanical properties of the mechanical resonator, as described in Ref. [5]; the corresponding coupling frequency is designed to be $\Omega = 2g/h \approx 110$ MHz. The equivalent electrical circuit for the combined resonator and qubit is shown in Fig. 2b.

Quantum Ground State

The completed device was mounted on the mixing chamber of a dilution refrigerator and cooled to $T \approx 25$ mK. At this temperature, both qubit and resonator should occupy their quantum ground states. To evaluate the system, we performed microwave qubit spectroscopy [23] to reveal the resonant frequencies of the combined system, using the pulse sequence shown in Fig. 2c. We measured the excited state probability P_e as a function of the qubit frequency (horizontal axis, in units of flux bias) and the microwave excitation frequency (vertical axis), as shown in Fig. 2d. The qubit frequency tunes as expected[23,30], and displays the characteristic level avoidance of a coupled system as its frequency crosses the fixed mechanical resonator frequency f_r. Similar observations have been made using optomechanical systems [33].

We note that the mechanical resonator produces two features in the classical transmission measurement shown in Fig. 1d, generating a maximum (f_r) and a minimum (f_s) in the response. When coupled and measured with the qubit as in Fig. 2, the lower frequency resonance f_s does not produce a response, as this resonance does not correspond to a sustainable excitation of the complete circuit. The higher frequency feature at f_r however does sustain such excitations, and thus appears in the spectroscopic measurement.

In order to determine the coupling strength between the qubit and the mechanical resonator, we fit the detailed behavior near the level avoidance, as shown in Fig. 2e. The fit qubit-resonator coupling strength $\Omega \approx 124$ MHz corresponds to an energy transfer (Rabi swap) time of about 4.0 ns, and is in reasonable agreement with our design value.

We performed a second spectroscopy measurement, similar to the qubit spectroscopy but coupling the microwaves to the mechanical resonator through the capacitor C_x (Fig. 2b), rather than to the qubit. In this measurement, shown in Fig. 3, the mechanical resonator acts as a narrow bandpass filter, so that significant qubit excitation (large P_e) should only occur near the mechanical resonance frequency f_r, as observed. In general, the spectrum looks very similar to that measured while exciting the qubit, providing strong support that the fixed resonance is indeed due to the mechanical resonator.

At higher microwave excitations, a new feature emerges in the resonator spectroscopy, as shown in Fig. 3b. The qubit, although approximated as a two-level system, actually has a double well potential with a small number of states in the left well, the two lowest being the qubit states $|g\rangle$ and $|e\rangle$, separated from the right well by a barrier whose height changes with flux bias. When the mechanical resonator is driven on resonance at higher excitation powers, there is sufficient energy to excite the qubit over the barrier and into the right well, yielding a large value for P_e even when the qubit energy level spacing is not resonant with the resonator. This effect is pronounced at more positive flux bias, where the barrier height is lower, and generates the distinct horizontal line in the right panel of Fig. 3b. From this line we obtain a precise determination of the resonator frequency, $f_r = 6.175$ GHz. We note further that the resonator frequency seen in this higher power measurement agrees with that revealed in the lower power measurement, as expected for a harmonic response.

These spectroscopic measurements are useful for probing the resonant modes of our circuit. However, although the qubit is a quantum device, the measurement is essentially classical, revealing little about the quantum behavior of the mechanical resonator. We therefore performed an additional experiment, using the qubit to probe the energy state of the resonator when no microwave signal was applied, essentially using the qubit as a quantum thermometer. This allowed us to verify with high precision that the resonator is actually in its ground state.

We initially prepared the qubit in its ground state $|g\rangle$, with a transition frequency $|g\rangle \leftrightarrow |e\rangle$ of 5.44 GHz, well out of resonance with the resonator, effectively turning off the qubit-resonator interaction. We then applied a flux bias pulse to bring the qubit to within $\Delta = f_q - f_r$ of the resonator frequency, and kept the qubit at this frequency for 1 μs. After returning the qubit to its original frequency, we measured the excited state probability P_e, as shown in Fig. 4. The qubit remains in its ground state for all values of Δ, with no detectable increase in P_e from its baseline value of 4%, even at resonance ($\Delta = 0$). We also display numerical predictions for the expected qubit P_e for a range of resonator phonon occupations $\langle n \rangle$. The expected response is peaked near zero detuning, and clearly even for small $\langle n \rangle$, exceeds the measured response by a substantial amount. We obtain a very conservative upper limit for the thermal occupation, $\langle n \rangle_{\max} < 0.07$ (see Supplementary Information).

As a check, we performed the same experiment but just prior to measuring the qubit, applied a microwave pulse to swap the qubit $|g\rangle$ and $|e\rangle$ populations. After this swap, the probability P_e is about 92%, independent of Δ, again demonstrating negligible additional excitation of the qubit, as otherwise P_e would drop near $\Delta = 0$.

This null result demonstrates that the resonator phonon occupation $\langle n \rangle \ll 1$, i.e. the resonator is with high probability in its quantum ground state.

Quantum Excitations

We next used our time-domain control of the qubit to create and measure individual quantum excitations in the resonator, allowing us to then measure the resonator's single-excitation energy and phase coherence times. We first characterized the qubit's energy relaxation time T_{1q} using the standard Rabi decay technique[23], described in detail in the Supplementary Information. From this measurement we find $T_{1q} \cong 17$ ns. This time is significantly shorter than for our typical qubits [31], $T_{1q} \sim 500$ ns, which we attribute here to dielectric dissipation in the aluminum nitride and the device substrate [34].

Despite the relatively short T_{1q}, the qubit coherence time was sufficient to perform quantum operations on the resonator. The coupling strength between the qubit and resonator is fixed at $\Omega = 2g/h \cong 124$ MHz, as discussed above. When the qubit and resonator are tuned on-resonance, energy will be exchanged (swapped) between the two at this frequency, with unit probability. When the qubit is detuned from the resonator by a frequency $\Delta = f_q - f_r$, the swap frequency increases to $\sqrt{\Omega^2 + \Delta^2}$, but the transfer probability should be reduced to $\Omega^2/(\Omega^2 + \Delta^2)$.

We generated an excitation in the resonator by first exciting the qubit and then swapping the excitation to the resonator, using the pulse sequence shown in Fig. 5a. The qubit was excited from $|g\rangle$ to $|e\rangle$ with a π-pulse, while the qubit was at its resting frequency of 5.44 GHz, detuned by $\Delta = -735$ MHz from the resonator. We then increased the qubit frequency towards the resonator frequency, performing the experiment for interaction detunings Δ ranging from -150 MHz (qubit below f_r) to +90 MHz. After a variable delay, the qubit was returned to its resting frequency and its excited state probability P_e was measured. This response was mapped out as a function of delay τ and detuning Δ, yielding the data in Fig. 5b, with simulations in the left panel and the experiment on right. Experiment and simulation are in good agreement.

When the qubit frequency is close to the resonator, we observe oscillations in $P_e(\tau)$. The oscillation period is longest at resonance $\Delta = 0$, and shortest at the largest values of $|\Delta|$, as anticipated; we fit the sequence of local maxima in P_e, as a function of τ and detuning, to the expected Lorentzian dependence for the swap period, as shown by the dash-dotted lines in Fig. 5b. The corresponding minimum swap frequency is found to be $\Omega = 132$ MHz, close to that determined from spectroscopy.

The amplitudes of the swap oscillations in P_e for $\Delta < 0$ are seen to be smaller than the corresponding amplitudes for $\Delta > 0$, not displaying the expected symmetric dependence for the transfer probability. This is due to the non-zero rise and fall times (~ 1 ns) of the frequency tuning pulse, which yields a higher swap efficiency for larger values of Δ: The qubit-resonator swap is initiated as the tuning pulse brings the qubit towards the resonator, swapping some of the qubit excitation into the resonator before the qubit is at the interaction frequency, and further continuing the swap when the qubit is returning to its resting frequency. This causes an interference that affects the swap visibility, with a reduction for small Δ, where the frequency tuning is proportionally more adiabatic than for larger Δ. Hence the exchange probability is maximized[35,36] for larger Δ. The simulations, which use trapezoidal tuning pulses to approximate the experiment, support this explanation; see Supplementary Information.

In Fig. 5c we show $P_e(\tau)$ for the interaction frequency indicated by the white dashed line in panel b. Five complete cycles are visible, where each minimum corresponds to a transfer of the excitation from qubit to resonator, and each maximum corresponds to a return of the excitation from resonator to qubit, with decay due to dissipation (see below). At $\tau = 0$, the system is in the state $|e0\rangle$, where the first state vector element represents the qubit and the second the resonator. At a quarter of the first Rabi oscillation, $\tau \cong 1.9$ ns, the qubit and mechanical resonator are entangled in the state $|g1\rangle + |e0\rangle$. At $\tau = \tau_{ph} \cong 3.8$ ns, the qubit state has been completely transferred to the mechanical resonator, generating a single phonon and leaving the system in the $|g1\rangle$ state. After a full Rabi period, $\tau = 2\tau_{ph} \cong 7.6$ ns, the excitation is exchanged back to the qubit, returning the system to the $|e0\rangle$ state with the resonator in its ground state.

The data shown in Fig. 5 provide clear and compelling evidence that we have created a single quantum excitation in a macroscopic mechanical object, and that the system's quantum coherence is sufficient to allow us to transfer this excitation multiple times between the qubit and the mechanical resonator. In this process, the system exists at times in an entangled qubit-resonator quantum state.

Using the ability to generate a single phonon, we next determined the resonator's energy relaxation time T_{1r} by injecting a single phonon into the resonator and measuring its decay, as shown in Fig. 6a and b. The results are fit using a resonator decay time $T_{1r} \cong 6.1$ ns, in reasonable agreement with the expected decay time $Q/2\pi f_r \approx 6.7$ ns from the classically-measured quality factor $Q \approx 260$.

We also attempted to measure the resonator's de-phasing time T_{2r}, as shown in Fig. 6c and d. This measurement is performed using a Ramsey fringe experiment, with the de-phasing time revealed by the evolution of the superposed state $|g0\rangle + |g1\rangle$, corresponding to the resonator simultaneously having zero and one phonon, i.e. this involves placing the mechanical system in a quantum superposition. The fit de-phasing time is $T_{2r} \sim 20$ ns, anomalously longer than the expected maximum $2T_{1r} \cong 12$ ns. This measurement is however relatively complex, requiring several pulses with good pulse control, and errors can result in longer-than-expected dephasing times; we can however conclude from this measurement that pure dephasing is not a dominant decay in and of itself.

In order to illustrate the resonator's bosonic nature, we also performed measurements in which we directly excited the mechanical resonator with a classical microwave pulse. With the qubit at its resting frequency, we applied a variable-amplitude Gaussian pulse to the resonator. The qubit was then brought into resonance with the resonator ($\Delta = 0$), and held there for an interaction time τ. Finally, the qubit was returned to its resting frequency and P_e measured.

Fig. 7 shows the resulting $P_e(\tau)$ as a function of the Gaussian pulse amplitude, along with the results of a quantum simulation (see Supplementary Information). As the microwave amplitude is increased, the frequency of the oscillations in P_e increases. This is a clear indication of the bosonic nature of the resonator, as the coupling strength between the qubit and the mechanical resonator is proportional to the number of phonons in the resonator [27,28,37]; the comparison with the simulation shows good agreement. We note that there was little or no direct microwave excitation of the qubit, as for small interaction times τ, the qubit was always measured to be in its ground state. We further note that if the resonator were instead behaving as a few-level quantum system, simulations demonstrate that the measured response would be markedly different, providing good evidence that the resonator is behaving as a harmonic system.

In conclusion, we have constructed a unique system for testing quantum mechanics in a mechanical system, comprising a 6 GHz mechanical resonator strongly coupled to a superconducting phase qubit. Spectroscopic measurements display the expected, but essentially classical, avoided-level crossing as the qubit is tuned through the mechanical resonator frequency. Employing the qubit as a quantum thermometer, we measured the residual resonator phonon number $\langle n \rangle$, demonstrating that there is no detectable excitation of the qubit due to the resonator. This constitutes strong evidence that we have succeeded in cooling a mechanical resonant mode to its quantum ground state. In addition, using time-domain control of the qubit, we have controllably created a single phonon state in the resonator, as well as entangled resonator-qubit states. Using the single-phonon capability, we have measured the mechanical resonator's energy relaxation time T_{1r}, and by creating a superposition state in the resonator, placed an upper limit on the dephasing time T_{2r}. A classical excitation of the resonator, by contrast, places it in a coherent state, also in good agreement with simulations. This set of measurements provide strong evidence that we have achieved reasonable quantum control over a macroscopic mechanical system. We note that full Wigner tomography of the resonator states, revealing quantum phase coherence for the entangled states[28], would provide further strong evidence of quantum behavior in this system; however, the resonator T_{1r} lifetime is too short, in comparison to the state preparation and measurement times, to permit such an analysis.

Methods

The mechanical resonator, made of AlN and Al, and the qubit, SQUID, and superconducting wiring, made of Al, were fabricated on an oxidized Si wafer using standard semiconductor processing. The wafer was diced into 6 mm square chips and placed in an aluminum mount, using wire-bonded electrical connections. Measurements of the resonator, shown in Fig. 1, were made at room temperature using a commercial microwave network analyzer. Qubit measurements of the resonator were made on a custom-built dilution refrigerator. The device mount was attached to the mixing chamber of a dilution refrigerator, and the device operated in vacuum at a temperature of 25 mK. Measurement cabling from room temperature to the device was heavily filtered and attenuated. Microwave signals were generated by a commercial microwave synthesizer, and were amplitude- and frequency-controlled using an I/Q modulator. Control signals for the modulator were generated by a high-speed digital-to-analog converter, controlled by a computer. The qubit and SQUID bias were generated using custom electronics controlled by computer via fiber optic lines. The SQUID measurement output was amplified and transmitted via fiber-optic to the same computer. Typical measurements of the excited state probability $P(e)$ involved accumulating of order 1,000 separate single-shot measurements. Full details may be found in the Supplementary Information.

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Figure 1 Dilatational resonator. **a,** Scanning electron micrograph of a suspended FBAR. Details for the resonator fabrication appear in the Supplementary Information. The mechanical structure was released from the substrate by exposing the device to xenon difluoride, which isotropically etches any exposed silicon; the suspended structure comprises, from bottom to top, 150 nm SiO_2, 130 nm Al, 330 nm AlN and 130 nm Al. The dashed box encloses the mechanically active part of structure. **b,** Illustration of the fundamental dilatational resonant mode for the mechanically active part of the resonator. The thickness of the structure changes through the oscillation cycle. **c,** Equivalent lumped element circuit representation of the mechanical resonator, based on a modified van Dyke-Butterworth model [26,38]. This circuit includes a series-connected equivalent mechanical inductance L_m and capacitance C_m, the parallel geometric capacitance C_0, with mechanical dissipation modeled as R_m and dielectric loss as R_0. **d,** Measured classical transmission $|S_{21}|$ (blue) and fit (red) of a typical mechanical resonance. The transmission displays two features, one at the frequency $f_s \approx 1/2\pi\sqrt{L_m C_m} \approx 6.07$ GHz due to the series resonance of the equivalent mechanical components L_m and C_m, the other at the slightly higher frequency $f_r \approx 1/2\pi\sqrt{L_m C_s} \approx 6.10$ GHz, due to L_m and the equivalent capacitance C_s of the capacitors C_m and C_0 in series; the expressions are approximate, as these ignore the effect of the dissipative elements and external circuit loading. Only the higher frequency mechanical mode f_r is involved in this experiment (see Supplementary Information). Inset: Equivalent circuit for the resonator embedded in the measurement circuit, including two on-chip external coupling capacitors $C_x = 37$ fF and an inductive element $L_s \approx 1$ nH that accounts for stray on-chip wiring inductance. Measurement is using a calibrated network analyzer that measures the transmission from port 1 to port 2. We calculate $C_0 = 0.19$ pF scaling from the geometry, and from the fit we obtain $C_m = 0.655$ fF, $L_m = 1.043$ μH, $R_m = 146\ \Omega$, and $R_0 = 8\ \Omega$. These values are compatible with the geometry and measured properties of aluminum nitride [29]. We calculate a mechanical quality factor $Q \approx 260$ and a piezoelectric coupling coefficient $k^2_{\rm eff} \approx 1.2\%$ [38].

Figure 2 Coupled qubit-resonator. **a,** Optical micrograph of mechanical resonator coupled to qubit (blemishes removed for clarity); fabrication details are in the Supplementary Information. **b,** Circuit representation. The Josephson junction is represented by a cross, with parallel loop inductance L_q and capacitance C_q, the latter including the parallel combination of a 1 pF interdigitated shunting capacitor and the junction capacitance (not shown). The resonator has $C_0 = 0.2$ pF coming from the geometry and AlN thickness of 300 nm, with coupling capacitance $C_c \approx 0.5$ pF. The capacitor $C_x = 0.5$ fF is used to couple external microwave signals to the resonator. The junction is modulated by magnetic flux applied through the flux bias wire FB, which controls the qubit $|g\rangle \leftrightarrow |e\rangle$ transition frequency. Microwave excitation of the qubit is also through FB. The shunting capacitor and the coupling capacitor C_c include a number of crossover shorting straps to eliminate potential electrical resonances. **c,** Qubit spectroscopy pulse sequence. The qubit (blue) is tuned to within $\Delta = f_q - f_r$ of the resonator (red) and a 1 μs microwave tone applied to the qubit; the qubit state is then measured in a single-shot manner using a flux-bias pulse, from which the excited state probability P_e is evaluated. **d,** Qubit spectroscopy, showing

P_e *vs.* flux bias (horizontal) and microwave frequency (vertical). The qubit frequency behaves as expected, with a prominent splitting as the qubit is tuned through the resonator frequency $f_r = 6.17$ GHz. Dashed box outlines expanded data shown in **e**, detail of qubit spectroscopy. Horizontal dash-dotted line shows resonator frequency f_r, with coupled mode frequencies fit by dashed lines, with fit coupling frequency $\Omega = 2g/h \approx 124$ MHz.

Figure 3 Resonator spectroscopy. **a,** Pulse sequence applied to qubit (blue) and mechanical resonator (red). The qubit is tuned to within Δ of the resonator frequency, and a 1 μs microwave tone applied to the resonator through C_x. The resulting qubit P_e is then evaluated. **b,** Left: Spectroscopic P_e as a function of qubit flux bias (horizontal scale) and applied microwave frequency (vertical scale). Right: Same as left panel but with higher microwave power, showing qubit state ejection due to interaction with a highly excited mechanical resonator. Qubit well level structure shown schematically as a function of flux bias, showing marginal excited state confinement at more positive flux bias. **Inset,** Detail for highest flux bias, with a very shallow well depth, highlighting qubit ejection at the resonant frequency of the mechanical resonator.

Figure 4 Qubit thermometry of resonator. **a,** Pulse sequence. Qubit in its ground state is tuned to within Δ of the resonator frequency for 1 μs, and in one set of measurements its excited state probability P_e then measured. In another set of measurements, a microwave swap pulse (X_π) was applied to the qubit prior to measurement, exchanging the $|g\rangle$ and $|e\rangle$ populations, followed by a P_e measurement. The detuning Δ was scanned over the range

± 210 MHz. **b,** Probability P_e with (green) and without (blue) the X_π pulse, as a function of detuning Δ. The mechanical resonance at f_r ($\Delta = 0$) is marked by the vertical dash-dot line, and the dashed lines are the numerically calculated P_e for different resonator mean phonon occupations $\langle n \rangle$ (see Supplementary Information); the shift in peak response from $\Delta = 0$ for larger $\langle n \rangle$ is due to the higher energy levels in the qubit, which come into resonance for $\Delta > 0$. Note that in the experiment, the resonator does not excite the qubit from its ground state, indicating the resonator itself is in the ground state.

Figure 5 Qubit-resonator swap oscillations. **a,** Pulse sequence used to generate quantum state exchange between the qubit and resonator. The qubit is initially in the ground state $|g\rangle$, at its resting frequency of 5.44 GHz, and is excited to the $|e\rangle$ state by a microwave π-pulse (X_π). The qubit is then brought to a detuning $\Delta = f_q - f_r$ from the resonator, and kept there for a time τ. After returning the qubit to its resting frequency, its excited state probability P_e is evaluated. Pulse sequence shown using compressed format, combining flux bias and microwave excitation. **b,** Qubit excited state probability P_e as a function of interaction time τ (horizontal axis) and detuning Δ (vertical axis), showing state transfer between the qubit and resonator, in which a qubit excitation is exchanged with a phonon in the mechanical resonator. Left panel shows simulations, right panel is experiment. Red dashed line is at resonator frequency f_r; white dashed line in right panel is for **c,** line cut through data for a fixed detuning ($\Delta = 72$ MHz, the value with the highest visibility swaps). Maxima correspond to the qubit being in its excited state, while minima correspond to state transfer to the resonator, creating a single phonon. The swap time needed to generate one phonon is $\tau_{ph} \cong 3.8$ ns. The nearly-complete swaps for $\Delta > 0$ are due to the time dependence of the tuning pulse, and the resulting complicated dynamics, as borne out by simulations; see Supplementary Information.

Figure 6 Resonator energy decay and dephasing times. **a,** Pulse sequence used to inject one phonon in the resonator and measure its decay. The qubit was first excited from $|g\rangle \rightarrow |e\rangle$ while at its resting frequency, using a microwave π-pulse. The qubit was then tuned to the interaction frequency of 6.25 GHz ($\Delta = 72$ MHz, the detuning chosen for the highest visibility swaps), and left there for the time τ_{ph}, transferring a phonon to the resonator and leaving the qubit in its ground state. After returning the qubit to its resting frequency for a time τ, the qubit was brought back to the interaction frequency for τ_{ph}, transferring any remaining excitation back to the qubit, and the probability P_e then evaluated. **b,** Measured $P_e(\tau)$, showing exponential decrease of the single-phonon state (blue points). We fit a mechanical resonator energy relaxation time $T_{1r} \cong 6.1$ ns (red line). **c,** Pulse sequence used to measure resonator phase coherence time; this is similar to **a**, except we replace the initial π-pulse by a $\pi/2$-pulse ($X_{\pi/2}$) to excite the $|g\rangle + |e\rangle$ qubit state, and after the second resonator transfer, use a second $\pi/2$-pulse ($\phi_{\pi/2}$) prior to measuring P_e, thus performing a Ramsey fringe measurement. The phase of the second $\pi/2$ pulse is swept at a rate that determines the frequency of the resulting oscillations. **d,** Measured P_e as a function of delay τ, representing dephasing in the mechanical resonator (blue dots), with a fit (red line) using a dephasing time $T_{2r} \sim 20$ ns.

Figure 7 Resonator coherent state. **a,** Pulse sequence to generate coherent phonon states. With the qubit at its resting frequency, an on-resonance Gaussian pulse of fixed duration (5.0 ns) and variable amplitude is applied to the resonator. The qubit is then tuned to $\Delta = 0$, left for an interaction time τ, and the qubit excited state probability P_e then evaluated. **b,** Measured $P_e(\tau)$ as a function of pulse amplitude (vertical axis, arbitrary units) and interaction time τ (horizontal axis). **c,** Simulation of coherent state evolution, with vertical axis in units of $\sqrt{\langle n \rangle}$, where $\langle n \rangle$ is the mean number of injected phonons; see Supplementary Information.