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Back-action-evading measurements of nanomechanical motion

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When carrying out ultrasensitive continuous measurements of position, one must ultimately confront the fundamental effects of detection back-action. Back-action forces set a lower bound on the uncertainty in the measured position, the 'standard quantum limit' (SQL). Recent measurements of nano- and micromechanical resonators are rapidly approaching this limit. Making measurements with sensitivities surpassing the SQL will require a new kind of approach: back-action-evading (BAE), quantum non-demolition measurement techniques. Here we realize a BAE measurement based on the parametric coupling between a nanomechanical and a microwave resonator. We demonstrate for the first time BAE detection of a single quadrature of motion with sensitivity four times the quantum zero-point motion of the mechanical resonator. We identify a limiting parametric instability inherent in BAE measurement, and describe how to improve the technique to surpass the SQL and permit the formation of squeezed states of motion.

When attempting to obtain complete knowledge of the dynamics of the position $x(t)$ of a simple harmonic oscillator, quantum back-action sets a lower bound of $x_{zp} = \sqrt{\hbar/2m\omega_m}$ on uncertainty Δx, the total added noise of the measurement expressed as an uncertainty in position[1,2]; m and ω_m are the mechanical resonator's mass and resonant frequency and $\hbar$ is the reduced Planck constant. The origin of this limit is the primitive fact that position and momentum are non-commuting observables, $[\hat{x},\hat{p}] = i\hbar$, and are linked through the equations of motion, $\mathrm{d}\hat{x}/\mathrm{d}t = -(i/\hbar)[\hat{x},\hat{H}]$, where $\hat{H} = (1/2)m\omega_m^2\hat{x}^2 + (1/2m)\hat{p}^2$ is the system Hamiltonian of an oscillator. During the theoretical investigations of the quantum limits of gravitational wave detectors over 30 years ago, it was realized that not all oscillator observables suffer from this fundamental limitation on measurement precision[3–5]. The two quadratures of motion $\hat{X}_1$ and $\hat{X}_2$ (where $\hat{x}(t) = \hat{X}_1\cos(\omega_m t) + \hat{X}_2\sin(\omega_m t)$) are non-commuting, $[\hat{X}_1,\hat{X}_2] = i\hbar/2m\omega_m$, but are not linked dynamically and are constants of the motion: $(\mathrm{d}\hat{X}_i/\mathrm{d}t) = (\partial\hat{X}_i/\partial t) - (i/\hbar)[\hat{X}_i,\hat{H}] = 0$. If one couples the detector only to $\hat{X}_1$, the back-action arising in a continuous measurement will disturb only the unmeasured quadrature $\hat{X}_2$, which is of no consequence to the evolution of $\hat{X}_1$. The proper coupling to the time-dependent observable $\hat{X}_1(t)$ can be achieved by using a 'slow' detector that responds only to signals of frequency $\ll 2\omega_m$, and by carefully modulating the coupling to position $\hat{x}$ (refs 6, 7). In principle, one may then increase the coupling strength arbitrarily without any back-action limit[6,8]. Such a single-quadrature BAE measurement may also be described as a quantum non-demolition (QND) measurement[3,5].

Position detectors formed by the parametric coupling between electrical and mechanical oscillators are readily adapted to such a measurement[7,8]. In such set-ups, BAE techniques are also immune to classical back-action forces created by electrical noise of non-ideal following amplifiers driving the electrical resonator, and are free from any detector-induced mechanical damping[6,7]. These techniques have been demonstrated on several gravitational wave detectors but only in a regime far from quantum mechanical limits[7], and recent measurements of nano- and micromechanical resonators approaching quantum limits[9–12] did not implement BAE techniques. A BAE scheme using the interference of two mechanical resonators in an optical cavity has also been shown to partially evade classical back-action[13,14]. The last scheme is however limited to a narrow, non-resonant frequency band, and does not allow squeezing or a true QND measurement. In this work, we demonstrate a continuous, broadband BAE scheme that allows resolution of a single quadrature near the zero-point motion, x_{zp}, and offer a path to QND quadrature detection with sensitivity below x_{zp}.

The approach we have taken uses a radiofrequency nanomechanical resonator coupled tightly to a microfabricated superconducting microwave resonator[15], and stimulated with a stream of microwave photons, shown in Fig. 1. (See also Supplementary Information.) Realization of these measurements requires a highly monochromatic microwave drive. We used cooled, high-Q, tunable copper cavities to filter the noise of our microwave sources, achieving suppression at 5.5 MHz from the carrier of -195 dBc Hz^{-1}, comparable to the best sources demonstrated[16]. Our nanomechanical resonator is formed from high-stress silicon nitride, which shows very low dissipation rates, with $Q > 10^6$ possible[17]. The device, having $\omega_m = 2\pi \times 5.57$ MHz, superconducting-resonator resonant frequency $\omega_{sr} = 2\pi \times 5.01$ GHz and mechanical and microwave damping rates $\Gamma_m/2\pi = 15$–25 Hz and $\kappa/2\pi = 494$ kHz respectively, was cooled in a dilution refrigerator and probed through carefully filtered, high-bandwidth cables using a low-noise high-electron-mobility-transistor microwave amplifier (noise temperature $T_N = 3.6$ K). Our device satisfies the sideband-resolved limit, $(\omega_m/\kappa) > 1$, which is essential to form a BAE transducer[7]. Similar devices have been used elsewhere to demonstrate back-action cooling[18–20] as well as continuous position detection having imprecision-limited $\Delta x = 21\, x_{zp}$ (ref. 21).

The expected quantum Hamiltonian of our system is given by:

$$\hat{H} = \hbar\left(\omega_{sr} + g\hat{x} - \frac{\lambda}{2}\hat{x}^2\right)\left(\hat{b}^\dagger\hat{b} + \frac{1}{2}\right) + \hbar\omega_m\left(\hat{a}^\dagger\hat{a} + \frac{1}{2}\right)$$

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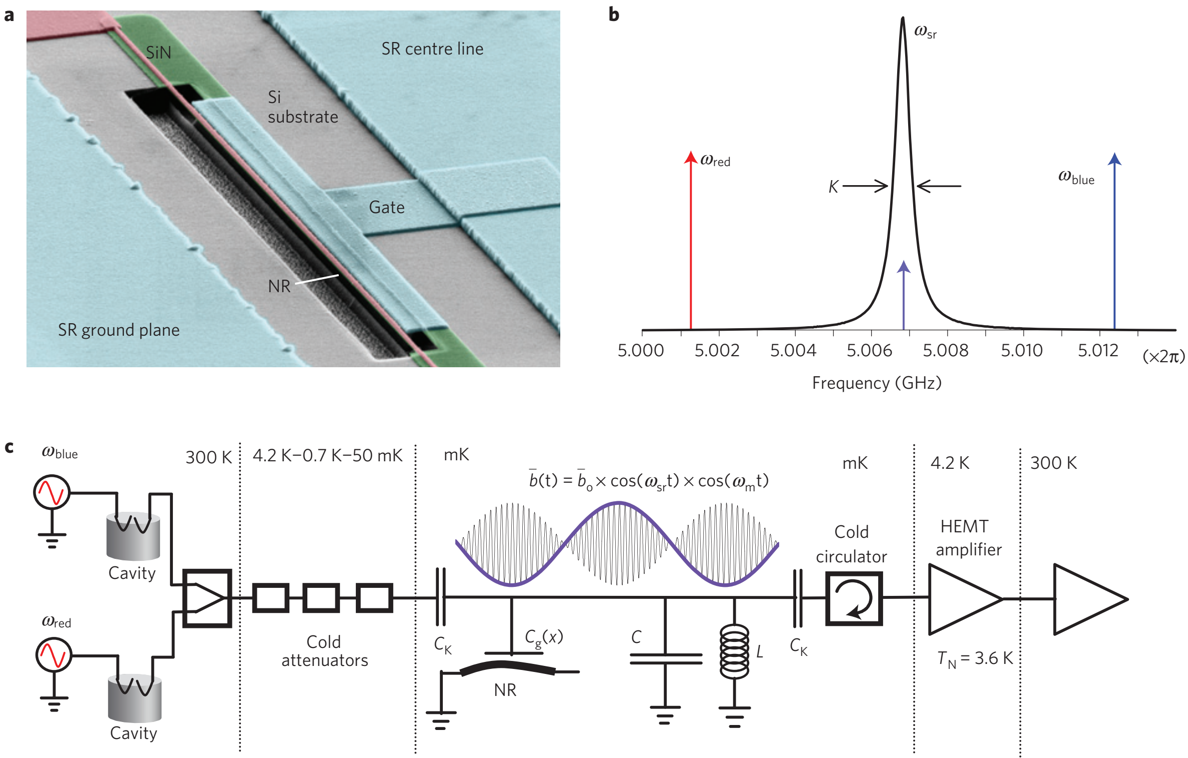

Figure 1 | Device and measurement scheme. a, A false-coloured scanning electron micrograph of our device: a 30 μm × 170 nm × 165 nm nanomechanical resonator (NR) (60 nm high-stress SiN, coated with 105 nm of Al) capacitively coupled (C_g, 85 nm gap) to a superconducting resonator (SR) formed by a 11.8-mm-long, 50 Ω co-planar waveguide (260-nm-thick Al on a high-resistivity (>10 kΩ cm) ⟨100⟩ Si chip) with a 16-μm-wide centre line and a coupling capacitor $C_\kappa \sim 4.5$ fF at each end. **b**, A measurement of the superconducting resonator transmission and the spectral location of the microwave pumps and up- and down-converted photons. **c**, A schematic of our cryogenic microwave measurement circuit. HEMT: high-electron-mobility transistor. Total capacitance $C_T = C + C_g + 2C_\kappa$.

where $\hat{a}(\hat{a}^\dagger)$ and $\hat{b}(\hat{b}^\dagger)$ are the mechanical and electrical oscillator annihilation (creation) operators. This form of Hamiltonian, parametrically coupling mechanical motion to the electromagnetic field in a resonant cavity, has been studied theoretically in both optical and microwave regimes[6,18,22–25]. The second term shows the parametric coupling of the superconducting resonator's frequency to the mechanical motion: $\hat{x} = x_{zp}(\hat{a}^\dagger + \hat{a})$ and $g = (\partial\omega_{sr}/\partial x) = (\omega_{sr}/2C_T)(\partial C_g/\partial x)$, where C_g is the coupling capacitance and C_T is the superconducting resonator's total effective capacitance. The term proportional to $\hat{x}^2$ results in frequency pulling of the mechanical resonator proportional to the square of the superconducting-resonator voltage (which itself is proportional to both the average superconducting resonator-energy and the microwave power circulating in the superconducting resonator; ref. 26), where $\lambda = (\omega_{sr}/2C_T)(\partial^2 C_g/\partial x^2)$. As we show below, this second-order term becomes important during BAE measurements. Both of these coupling terms may be understood in terms of the charge q on the superconducting resonator and its capacitive energy $q^2/2C_T$ in the limit $C_g \ll C_T$.

Harmonic motion of the nanomechanical resonator modulates the superconducting-resonator resonant frequency, and thus pumping the superconducting resonator at $\omega_{red} = \omega_{sr} - \omega_m$ results in up-conversion of the pump photons to ω_{sr}, whereas pumping at $\omega_{blue} = \omega_{sr} + \omega_m$ results in down-conversion[22,27]. To calibrate the magnitude of the resulting microwave sideband at frequency ω_{sr} in terms of mean-squared position $\langle x^2 \rangle$, we exploit equipartition, $k_B T = m\omega_m^2 \langle x^2 \rangle$, by recording the linear dependence of sideband power on fridge temperature T, similarly to techniques used elsewhere[9,19,28]. From this measurement we determine $g = 2\pi \times 7.5$ kHz nm^{-1} and $C_g = 253$ aF. By further measuring ω_m as a function of pump power, we find $\lambda = 2\pi \times 0.15$ kHz nm^{-2}.

We first consider the performance of our system in a non-BAE configuration, using only a single-tone cavity drive. An up- (down-) converted photon is a result of the absorption (emission) of one mechanical quantum; these processes lead to an increase (decrease) of nanomechanical-resonator damping by an amount Γ_{opt} as well as a corresponding nanomechanical-resonator cooling (heating)[9,18,22,29–33]. Figure 2 shows that the resulting measured values of both the total nanomechanical-resonator damping rate, $\Gamma_{tot} = \Gamma_m + \Gamma_{opt}$, and occupation factor, $\bar{n}_m$, closely follow theoretical predictions[22]. The sideband produced is a measure of both quadratures of the mechanical motion and subject to the usual SQL on position detection[7,34]. We may compute the sensitivity Δx as an imprecision attributable to added noise, by applying our thermal calibration to the noise spectral density S_{bgd} contributed by our amplifier. This is equivalent to taking $\Delta x = \sqrt{(k_B T_m/m\omega_m^2)(S_{bgd}/S_{sideb}(\omega_{sr}))}$, where $S_{sideb}(\omega_{sr})$ is the peak sideband amplitude and T_m is the temperature of the mechanical mode[28,35]. Thus, $\Delta x/x_{zp}$ may be calculated without reference to the nanomechanical-resonator mass. Figure 3 shows that when we apply the largest possible pump powers at $\omega = \omega_{red}$, with $\bar{n}_p$ (the occupation of the superconducting resonator owing to pumping) reaching $\sim 2 \times 10^8$, we find that the position uncertainty approaches a limiting value of $\Delta x = 6.7\ x_{zp}$ owing to the increase in back-action damping of the nanomechanical resonator. This limiting resolution can be reduced only by using a superior microwave detector and not by improving the nanomechanical-resonator properties or the coupling to the superconducting resonator[36]. Note that for this single-sideband measurement, back-action limits the sensitivity Δx only by increasing the nanomechanical-resonator damping[35]. The force sensitivity of our device is

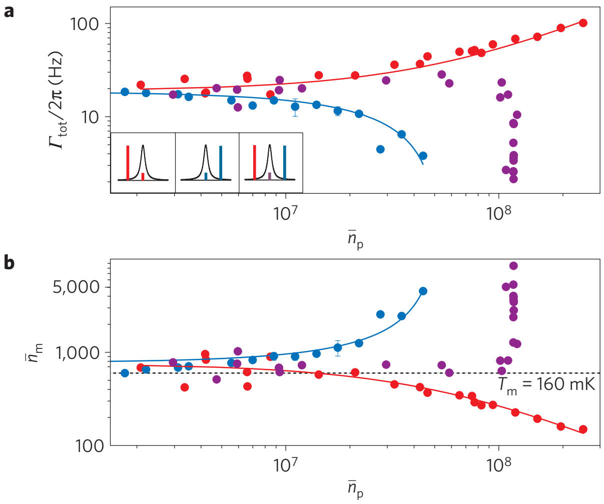

Figure 2 | Mechanical linewidth and occupation factor versus pump occupation. a,**b**, Linewidth, Γ_{tot} (**a**), and occupation factor, $\bar{n}_m$ (**b**), versus superconducting resonator pump occupation $\bar{n}_p$. Thermal-driven motion of a nanomechanical resonator measured at a fridge temperature of 142 mK using a single pump tone at frequency ω_{red} (red points) or ω_{blue} (blue points), or a double pump, BAE configuration (purple points). The error bars represent $1-\sigma$ confidence bounds of Γ_{tot} and sideband area in Lorentzian fits of measured sidebands. (See Supplementary Information.) The solid lines show fits to expressions in ref. 22. In the double-pump configuration, parametric amplification of nanomechanical-resonator motion becomes significant for pump strengths $\bar{n}_p > 10^8$; drifts in Γ_m and ω_m result in scatter in the parametrically amplified Γ_{tot} and $\bar{n}_m$. Insets: Spectral arrangement of pumps and sidebands relative to the microwave resonance.

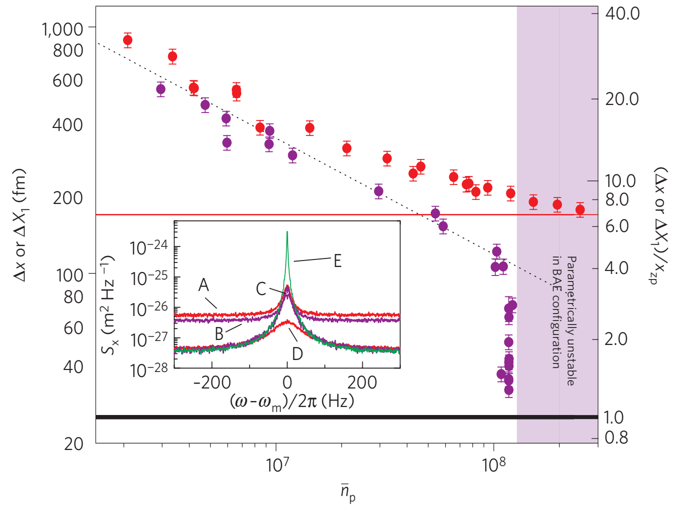

Figure 3 | Measured position sensitivity Δx or ΔX_1 versus superconducting resonator pump occupation. The pump configurations and symbols are the same as in Fig. 2. The error bars represent the combined uncertainties in S_{bgd} and Γ_{tot} derived from Lorentzian fits of measured sidebands. The horizontal red line shows the limiting sensitivity for a single pump tone. The slanted black line shows the expected sensitivity with no back-action damping. The shaded region is inaccessible to BAE owing to parametric instability. Inset: Thermally driven nanomechanical-resonator-position spectra, for a red pump (A: $\bar{n}_p = 8.5\times10^6$, D: $\bar{n}_p = 1.2\times10^8$), BAE pumps (B: $\bar{n}_p = 9.4\times10^6$, C: $\bar{n}_p = 1.1\times10^8$), or parametrically amplified by BAE pumps (E: $\bar{n}_p = 1.2\times10^8$).

limited by thermal motion of the nanomechanical resonator to 1.7×10^{-18} N Hz$^{-1/2}$ at a measurement temperature of 142 mK, achieving 8×10^{-19} N Hz$^{-1/2}$ at 60 mK, comparable to the best force sensitivities achieved elsewhere[9,37].

We now turn to the heart of this article, our BAE measurement. To achieve sensitivity to only a single mechanical quadrature, we apply equal-intensity phase-coherent pumps at both ω_{red} and ω_{blue}, such that the up- and down-converted sidebands coherently interfere. In this case, the field within the superconducting resonator is modulated at the nanomechanical-resonator resonant frequency: $\bar{b}(t) = \bar{b}_0 \times \cos(\omega_{sr}t) \times \cos(\omega_m t)$ (refs 6, 7). Figure 2 demonstrates that the combined ω_{red} and ω_{blue} pumps balance the rates of photon up- and down-conversion, producing no back-action damping; thus, for pump strengths below about $\bar{n}_p = 10^8$, Γ_{tot} and $\bar{n}_m$ are independent of $\bar{n}_p$. Furthermore, the relative phase between the two cavity drive tones picks out a single mechanical quadrature to detect, as illustrated schematically in Fig. 1c. By driving the mechanical resonator with an electrostatic force at frequency ω_m, we see that the detected signal depends sinusoidally on the relative phase between the modulation of the cavity field, $\cos(\omega_m t)$, and the nanomechanical-resonator motion (Fig. 4b). In this way, the signals that are detected and amplified yield information about only X_1 and not X_2.

To demonstrate the BAE nature of this scheme, we inject frequency-independent voltage noise (generated by a chain of noisy amplifiers) into the superconducting resonator and record the output spectrum, with results shown in Fig. 4a. The resulting induced cavity fluctuations act as a classical source of back-action; however, when the cavity is also driven by the two BAE drive tones, this back-action is expected to drive motion only in X_2 and not in X_1 (ref. 38). To demonstrate this effect and estimate the BAE effectiveness, we make a measurement in two stages. We first pump with double tones as well as the injected noise. We observe no mechanical signature in the output noise, indicating that the measured X_1 amplitude is indeed unaffected by the induced cavity noise (to within uncertainty defined by the standard error in the measured noise amplitude). Slow drifts of up to 5 Hz in the nanomechanical-resonator frequency limit the averaging time and therefore the resolution of X_1 fluctuations. We next carry out a non-BAE measurement by shutting off the blue pump tone, leaving only a single tone at ω_{red}, but making no other changes. The measurement is now equally sensitive to both quadratures of motion; furthermore, the 'classical back-action' associated with the cavity noise will drive both X_1 and X_2 quadratures[7]. In this configuration, this back-action-driven mechanical motion produces a sideband signal out of phase with the fluctuating cavity voltage, resembling noise 'squashing' behaviour reported elsewhere[39]. The sideband representing the back-action-driven motion reduces the output noise spectrum $S_n(\omega)$ at $\omega \simeq \omega_{sr}$ by a factor of $(1-\Gamma_{opt}(\Gamma_m+\Gamma_{tot})/(4(\omega-\omega_{sr})^2+\Gamma_{tot}^2))$, from which we may calculate the back-action-driven mechanical amplitude. (See Supplementary Information.)

Using the results of this non-BAE measurement, we can now extract the magnitude of the unseen X_2 quadrature in the original BAE configuration; this is possible as we use the same injected noise in both measurements. We can express the efficiency R of the BAE measurement in terms of the noise-driven variances $\langle X_1^2\rangle$ and $\langle X_2^2\rangle$. For perfect BAE, $R = \langle X_1^2\rangle/\langle X_2^2\rangle = 0$, whereas for no BAE it would be 1; we find that R is at most 1.2×10^{-2}. This value represents a worst-case estimate based on a value of $\langle X_1^2\rangle$ equalling the statistical uncertainty of the BAE measurement in Fig. 4a; our measurements are also consistent with $R = 0$. In principle, the limiting value of R is $(1/32)(\kappa/\omega_m)^2$, or $\simeq 2.4\times10^{-4}$ for our device[6,7]. In Fig. 4c, we illustrate in an $X_1 - X_2$ phase-space plot the relative quadrature amplitudes calculated from Fig. 4a. Here the BAE X_1 amplitude again represents only a worst-case value.

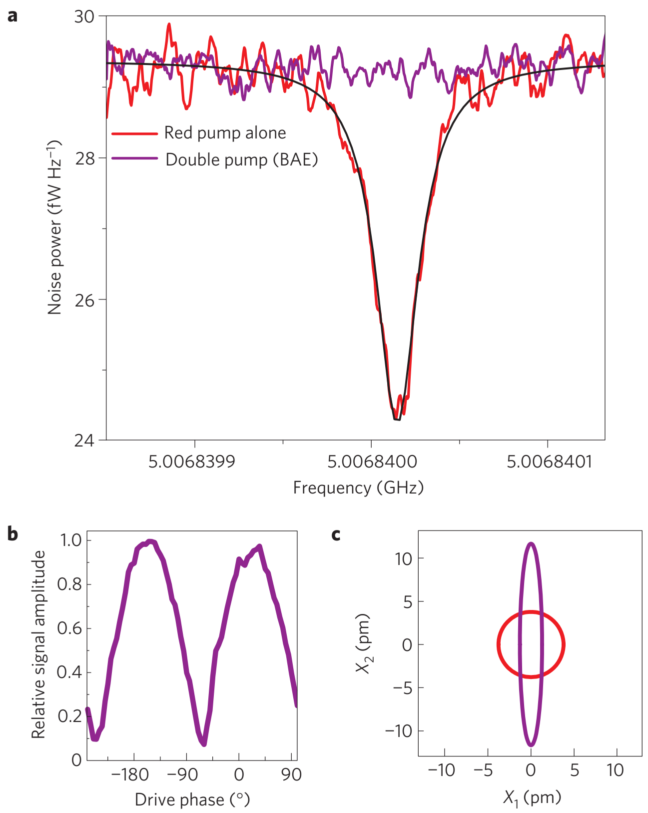

Figure 4 | Single-quadrature detection and BAE. a, The power spectrum near ω_{sr} with noise injected to a level 36 dB above the amplifier noise floor. The response to a single red pump tone ($\bar{n}_p = 1.2 \times 10^7$) shows a 'hole' in the noise (red line data, black line Lorentzian fit) owing to back-action-driven motion of the nanomechanical-resonator correlated with the superconducting-resonator fluctuating noise voltage. The response to BAE pumps ($\bar{n}_p = 2.4 \times 10^7$) shows no back-action-driven motion (purple line) in the measured quadrature. **b**, Sensitivity to only one quadrature of driven nanomechanical-resonator motion. **c**, Nanomechanical-resonator amplitude in an $X_1 - X_2$ phase-space plot, calculated from measurements in **a**. The BAE X_1 amplitude here is only an upper bound.

Figure 3 shows the uncertainty ΔX_1 of the single-quadrature BAE measurement, determined solely by the background noise floor (that is, measurement imprecision), as no back-action contribution is expected or detected. The inset shows examples of the corresponding measured position spectra. The uncertainty in this case improves continuously with increasing $\bar{n}_p$, achieving $\Delta X_1 = 4.1\ x_{zp}$ at $\bar{n}_p = 1.1 \times 10^8$. The added noise of our amplifier is a principal limiting factor here; if we could have used a quantum-limited voltage amplifier, ΔX_1 would instead be $1.1 x_{zp}$. Further limitations arise from ∼1.5 dB of signal loss between the superconducting resonator and the amplifier, as well as from dissipation within the superconducting resonator, which contributes ∼40% of the total κ. Eliminating these factors would further suppress ΔX_1 to $0.7 x_{zp}$. We believe this is the first time that a single-quadrature BAE measurement of a mechanical oscillator has realized sufficiently high coupling strength to reach this quantum regime. As we discuss below, even with such limiting factors, relatively straightforward improvements of our device would readily allow $\Delta X_1 < x_{zp}$. In contrast, a standard continuous position measurement (for example, made using a single pump at the cavity resonance[10,21,40,41]) could never achieve sensitivity below x_{zp} because of an unavoidable back-action contribution to Δx. It is also useful to parameterize the BAE measurement strength by n_{BA}, the quantum back-action heating of X_2 (expressed as a number of quanta). At our maximum measurement strength, we find that $n_{BA} = 1.7$. For an ideal superconducting resonator readout and the nanomechanical resonator initially in its ground state, this strength of measurement would result in a conditionally squeezed state with $\Delta X_1 = 0.64\ x_{zp}$ (ref. 6).

In the BAE configuration, the constancy of $\bar{n}_m$ for pump powers below $\bar{n}_p \simeq 10^8$ indicates no thermal heating of the nanomechanical resonator by the radiofrequency pump field or other classical back-action effects. However, at higher pump powers, we find both linewidth narrowing and a marked increase in nanomechanical-resonator noise temperature (Fig. 2 and Fig. 3, inset). This effect is explained by the pump power in this configuration being effectively modulated at $2\omega_m$, driving a degenerate parametric amplification of the nanomechanical resonator through the consequent periodic frequency pulling of the nanomechanical resonator[26]. When the size of the periodic nanomechanical-resonator frequency shift becomes comparable to Γ_m (ref. 42), the amplification becomes significant, increasing with pump power until the nanomechanical resonator self-oscillates. As the parametric amplification and de-amplification occur in a basis that is rotated by $\pi/4$ from the measured quadrature X_1, in this regime the measurement is not back-action evading. A reduced Δx (as low as 1.3 x_{zp}) results in this regime from the narrowed nanomechanical-resonator linewidth but comes at the expense of amplified thermal motion.

The techniques demonstrated here show the value of back-action engineering when carrying out strong measurement. In an improved device, we expect these techniques to enable significant advancements in the area of quantum state preparation and measurement of a mechanical device. We have demonstrated elsewhere[20] that by using a higher-impedance superconducting resonator waveguide, making $\omega_{sr} = 2\pi \times 7.5$ GHz and increasing C_g to 450 aF, the coupling factor g may be increased to 84 kHz nm^{-1}. By further increasing ω_{sr} to $2\pi \times 10$ GHz and reducing κ to $2\pi \times 250$ kHz, keeping all other device parameters the same, we expect to be able to realize sensitivity to one quadrature of $\Delta X_1 = 0.5 x_{zp}$. This would allow the realization and study of squeezed mechanical states[6], which can be useful for ultrasensitive detection and also provide a quantitative measurement of decoherence[43].

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Author contributions

J.B.H., T.R. and T.N. contributed equally to the execution and analysis of this work. M.S. built key apparatus. A.A.C. provided analysis and theoretical support. K.C.S. designed and oversaw all aspects of the work.

Additional information

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