Stationary entangled radiation from micromechanical motion

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Mechanical systems facilitate the development of a hybrid quantum technology comprising electrical, optical, atomic and acoustic degrees of freedom4, and entanglement is essential to realize quantum-enabled devices. Continuous-variable entangled fields—known as Einstein–Podolsky–Rosen (EPR) states—are spatially separated two-mode squeezed states that can be used for quantum teleportation and quantum communication2. In the optical domain, EPR states are typically generated using nondegenerate optical amplifiers5, and at microwave frequencies Josephson circuits can serve as a nonlinear medium4,6. An outstanding goal is to deterministically generate and distribute entangled states with a mechanical oscillator, which requires a carefully arranged balance between excitation, cooling and dissipation in an ultralow noise environment. Here we observe stationary emission of path-entangled microwave radiation from a parametrically driven 30-micrometre-long silicon nanobeam oscillator, squeezing the joint field operators of two thermal modes by 3.40 decibels below the vacuum level. The motion of this micromechanical system correlates up to 50 photons per second per hertz, giving rise to a quantum discord that is robust with respect to microwave noise7. Such generalized quantum correlations of separable states are important for quantum-enhanced detection8 and provide direct evidence of the non-classical nature of the mechanical oscillator without directly measuring its state9. This noninvasive measurement scheme allows to infer information about otherwise inaccessible objects, with potential implications for sensing, open-system dynamics and fundamental tests of quantum gravity. In the future, similar on-chip devices could be used to entangle subsystems on very different energy scales, such as microwave and optical photons.

Radiation pressure and back-action can give rise to entanglement and squeezing between electromagnetic radiation and a mechanical resonator10,11. Recent experiments have demonstrated single-mode squeezed states of mechanical motion12,13 and radiation fields at both optical14–16 and microwave17 frequencies. Very recently, entanglement between photons and a mechanical oscillator18 and between two mechanical oscillators19,20 have been realized. Here we present results that confirm the prediction that massive mechanical objects can deterministically produce path-entangled radiation21–25. Using a highly versatile silicon-on-insulator electromechanical platform that is compatible with on-chip photonic14,26 and phononic27 crystal cavities, we demonstrate the generation of stationary entangled states between the propagating output fields of two microwave resonators separated by 1 m in a millikelvin environment. The substantial brightness of the mechanical squeezed facilitates our tomography measurement and proves the robustness of quantum discord in the presence of noise in the microwave domain.

We consider a three-mode electromechanical system in which two microwave cavities with resonance frequencies ωm± and total damping rates γm with i = 1, 2 are coupled to a vibrational mode with resonance frequency ωm and intrinsic damping rate γm, as shown schematically in Fig. 1a. The electromagnetic field of the microwave resonators exerts radiation pressure on the mechanical resonator. In return, the vibration of the mechanical resonator mediates a retarded interaction between the microwave modes. In the presence of two strong microwave pumps with frequencies ωLU = ωL± + ωm, as indicated in Fig. 1b, we can linearize the system and describe its physics in reference frames rotating at frequencies ωL± and ωm with the Hamiltonian

\[ H = G_1(b_i^†c_i^† + c_i) + G_2(bc_i^† + c_i^*b) \]  

(1)

where \( h = 1 \), \( c_i \) and \( c_i^\dagger \) are the annihilation operators for cavity i and the mechanical oscillator, correspondingly, and \( G_1 = g_{m,i}/\sqrt{\kappa_i} \) and \( g_{m} \) are the effective and vacuum electromechanical coupling rates between the mechanical mode and cavity i, respectively. \( n_i \) is the number of photons in resonator i due to a drive with detuning \( \Delta_\omega = \omega_{c,i} - \omega_{m} \). Here we assume the regime of fast mechanical oscillations, \( \omega_m \gg \{n_i, G_1\} \), which allows us to neglect the fast-oscillating terms at ±2ωm. The first term in equation (1) describes a parametric down-conversion interaction that is responsible for entangling microwave resonator 1 with the mechanical oscillator. The second term describes a beam-splitter interaction between the mechanical resonator and microwave resonator 2, which exchanges the states of the electromagnetic and mechanical modes. If the electromagnetic coupling rate, \( 4G_1^2/\kappa_\omega \), exceeds the decoherence rate of the mechanical resonator, \( \gamma_m/\kappa_\omega \), with the mechanical bath occupancy \( \bar{n}_m = (e^{\hbar\omega_m/kT_B} - 1)^{-1} \) (\( k_B \) is Boltzmann’s constant and \( T_B \) is the device temperature), the output of both microwave resonators is mapped into a two-mode squeezed thermal state23, which can also be understood in the context of reservoir engineering24.

We experimentally realize the described entanglement generation scheme in a hybrid dielectric–superconducting electromechanical system. The circuit, shown in Fig. 2a, consists of a metallized silicon nanobeam resonator whose vibrational in-plane mode at \( \omega_m/2\pi = 2.81 \) MHz (with an intrinsic damping rate of \( \gamma_m/2\pi = 4 \) Hz and a bath occupation of \( \bar{n}_m = 77 \)) is capacitively coupled to two high-impedance superconducting coil resonators at \( \omega_{c,1}/2\pi = 10.17, 12.13 \) GHz with energy decay rates \( (\kappa_{c,1}, \kappa_{c,2})/2\pi = (0.52, 0.48) \) MHz and waveguide to resonator coupling ratios \( (\eta_1, \eta_2) = (0.76, 0.67) \). Large vacuum electromechanical coupling strengths of \( (g_{m,1}, g_{m,2})/2\pi = (152, 170) \) Hz are achieved for this three-mode electromechanical system by suspending and substantially miniaturizing the geometric inductors (see Methods for more details).

The output of each resonator passes through two different measurement lines, as shown in Fig. 2b. After amplification, the signals are filtered and down-converted to an intermediate frequency of 2 MHz, and digitized with a sampling rate of 10 MHz using an 8-bit analog-to-digital converter (ADC). The reflected pumps are cancelled to avoid any amplifier compression. The fast Fourier transform-based fast Fourier transform-based method is used to compute the quadrature output fields. To this end, we extract the quadratures \( \hat{X}_i = (d_i + d_i^\dagger)/\sqrt{2} \) and \( \hat{P}_i = (d_i - d_i^\dagger)/\sqrt{2} \) with the scaling factors \( \xi_i = g_i/\sqrt{\eta_i} \) and \( \eta_i = g_i/\sqrt{\eta_i} \), where \( d_i \) is the propagating resonator output mode and \( g_i \) is the total system gain of the output channel i, \( B = 100 \) Hz is the digitally chosen...
measurement bandwidth and $R = 50$ Ω is the input impedance of the ADCs. We calibrate the system gain ($G_p$, $G_c$) = (83.20(06), 79.99(08)) dB and system noise ($n_{add,1}$, $n_{add,2}$) = (8.3(1), 11.5(2)) of both measurement channels as described in Methods (errors are statistical 95% confidence interval values). We use these values for all following measurements, which determines the effective points of signal detection to be 0.5 m from the resonator outputs and approximately 1 m apart from each other, as shown in Fig. 2b. Beyond this point, the generated states are exposed to amplifier noise, additional losses and a high-temperature thermal bath.

The non-classicality of such Gaussian states can be fully characterized by the $4 \times 4$ covariance matrix $V$, a symmetric matrix with 10 independent elements. The diagonal elements of $V$ are calculated from the variances of the scaled quadratures when the pumps are on and off, that is, $V_u = \langle u^2 \rangle_{on} - \langle u^2 \rangle_{off} + \frac{1}{2} \coth \frac{n_i}{2} k_B T$, where $u \in \{X_1, P_1, X_2, P_2\}$, $\frac{1}{2} \coth \frac{n_i}{2} k_B T \approx 0.5$ is the input quantum noise at temperature $T$, and the brackets $\langle \ldots \rangle$ denote an average over all of the 216,000 (604,800) measurements made when the pumps were on (off). The off-diagonal elements of the covariance matrix are specified by the covariances of the two modes, $V_{ij} = \langle u_i u_j \rangle_{on} / 2$, which are zero when the pumps are turned off. The degree of two-mode squeezing is best visualized using the quasi-probability Wigner function

$$W(\psi) = \frac{\exp(-\frac{1}{2}(\psi \psi^*)^4)}{\pi^2 \det(V)}$$

with the state vector $\psi = (X_1, P_1, X_2, P_2)$. Figure 3a shows the two relevant Wigner function projections of the measured covariance matrix in blue and the ideal vacuum state $V_{vac} = I/2$ in red ($I$ is the identity matrix). The $\{X_1, X_2\}$ and $\{P_1, P_2\}$ projections clearly show cross-quadrature two-mode squeezing below the quantum limit in the diagonal directions. For this measurement, microwave resonator 1 (2) is driven from the blue (red) sideband with a coherent drive power of $P_b = -87.1$ dBm ($P_b = -84.4$ dBm) at the device input, corresponding to single-cavity cooperativites $C_1 = 4G_1^2/k_B \gamma_m$ of $C_1 = 100.5$ ($C_2 = 170.2$). The raw data of the measured Gaussian phase space representation—that is, the two-variable histograms representing the probability distribution of all possible combinations of the measured quadratures $\{X_1, P_1, X_2, P_2\}$—are discussed in Methods.

To quantitatively assess the degree of squeezing we define the EPR operator pair $X_{\varphi} = [X_1(\varphi) - X_2(\varphi)]/\sqrt{2}$ and $P_{\varphi} = [P_1(\varphi) + P_2(\varphi)]/\sqrt{2}$, where $\varphi$ represents a rotation of the detector phase in channel 1, implemented during post-processing. For each rotation angle we evaluate the squeezing parameters $\langle X_{\varphi}^2 \rangle = \langle V_{11} + V_{33} - 2V_{13} \rangle / 2$ and $\langle P_{\varphi}^2 \rangle = \langle V_{22} + V_{44} + 2V_{24} \rangle / 2$, as shown in Fig. 3b. For one common optimal rotation angle we find that the two operators are squeezed by 3.43(75) dB and 3.36(74) dB, respectively, below the vacuum level. The phase dependence shows squeezing and anti-squeezing, as expected for a two-mode squeezed applied to a thermal Gaussian state (solid lines)

$$S(\varphi) = \frac{(1 + n_1 + n_2) \cos(2\varphi) - \sin(2\varphi) \cos(\varphi)}{2}$$

with the effective thermal photon inputs $n_1 = 1.43$ and $n_2 = 2.49$ fully constrained by the measured output photon numbers $V_{11} = 12.83$ and $V_{33} = 13.89$, and the fitted squeezing parameter $r = 1.19$ in agreement with the measured number of correlations $V_{13} = 13.13$; see Supplementary Information for more details.

To verify the existence of entanglement between the two output modes we use the Duan criterion. The two-mode Gaussian state is entangled if $\Delta_{EPR} = \langle X_1^2 \rangle + \langle P_1^2 \rangle < 1$ and it is in a vacuum state for...
\(\Delta_{EPR} = 1\). In Fig. 3c we show measurements of \(\Delta_{EPR}\) for the optimal angle \(\varphi\) as a function of the red-detuned drive power \(P_r\) and the calculated difference between the red and blue cooperativities, \(C_2 - C_1\). For small \(P_r\) the system is predicted to be unstable (blue-shaded region) and the measured values exceed the range of the plot. At a cooperativity difference of 70, the mechanical mode is sufficiently cooled, the in separability condition is fulfilled and we find a minimum of \(\Delta_{EPR} = 0.46(8)\), which clearly proves that the radiation emitted from the electromechanical device is entangled before leaving the millikelvin environment. For comparison, the same squeezing parameter \(r = 1.19\) would give rise to \(\Delta_{EPR} = 0.09\) for an ideal squeezer with a vacuum state at its input \(\Delta_0 = 0\). By increasing the red-detuned drive \(P_r\), the parameter \(\Delta_{EPR}\) eventually goes above the vacuum limit and the state becomes separable. We assign this effect to the pump-power-dependent excitation of two-level systems that populate the microwave cavity with uncorrelated noise photons, which can result in a degradation of quantum correlations. We carefully rule out amplifier nonlinearities with detuned pump-on measurements, which would lead to the opposite effect (lower \(\Delta_{EPR}\) at higher pump power). The reported errors are the statistical errors of the measured means, which exceed the statistical errors and the measured long-term variation of the subtracted noise measurement (pump turned off), as well as the error of the calibration measurements.

To quantitatively describe the power dependence of the EPR parameter \(\Delta_{EPR}\), shown in Fig. 3c, we fit the data with a full theoretical model outlined in Supplementary Information, which also takes into account the detection bandwidth and filter function. At small pump powers above the instability, we find excellent agreement with theory (blue solid line) using only the independently verified device parameters reported above. We quantify the degree of mechanically generated entanglement with the logarithmic negativity representing an upper bound on the distillable entanglement. The maximum measured entanglement in our system is \(E_N = 1.07(36)\), and the useable distribution rate of entangled EPR pairs (127 entangled bits per second) can be calculated using the entropy of formation, \(E_F = 0.45\), and the bandwidth of the emitted radiation, \(\gamma_{eff}/2\pi = 282\) Hz.

The quantum discord \(D\) expands the concept of quantum correlations to include separable states\(^{29,30}\). \(D > 0\) indicates the presence of correlations that originate from the noncommutativity of quantum operators, which also applies to mixed states. Quantum discord has been shown to be a valuable resource for sensing, cryptography and quantum phase estimation and, compared to entanglement, is expected to be more resilient to a dissipative bath\(^7\). Figure 3c shows the extracted \(D\) with (red) and without (blue) subtraction of the calibrated system noise. Without the presence of noise the discord is relatively stable owing to the power-dependent competition of noise and cooling. It peaks at \(D \approx 1.5\) for the drive power at which the entanglement is maximal. For comparison, the discord of an ideal squeezer with a vacuum state at its input is \(D = 2.7\). Interestingly, even when no amplifier noise is subtracted, we measure a positive discord over the full range—a hallmark of the nonclassical origin of the measured correlations. The maximum \(D = 0.037(4)\) is obtained close to the instability region at \(C_2 - C_1 = 23\), where the correlated output photon numbers \(V_{11} = 55.25\) and \(V_{24} = -55.41\) are maximal, as shown in the inset. The results are in excellent agreement with the theory provided in Supplementary Information over the full range of power, and show that in the presence of noise higher numbers of correlated output photons can result in a larger discord, even if the degree of squeezing and entanglement is lower.

It has recently been shown that the measured stationary entanglement between output modes implies that the mediating macroscopic mechanical oscillator is a non-classical object that must have shared quantum correlations—in the form of discord—with the two microwave modes for a finite time before reaching the steady state\(^5\). In the future, such a noninvasive technique could be used to determine the nature of other inaccessible or difficult-to-control mediators, such as the gravitational field or sensitive biological systems. In the near term, the presented mechanical entangler can help to harness the capabilities...
of superconducting circuits at elevated temperatures. On the one hand, an analogous microwave–optical implementation with a photonic crystal cavity could be used to optically distribute entangled states between cold superconducting nodes. On the other hand, we find that our cold electromechanical system produces noise-resistant quantum field correlations with $D > 0$ that could find use in quantum-enhanced microwave sensing applications, potentially even at room temperature.

**Online content**

Any methods, additional references, Nature Research reporting summaries, source data, statements of data availability and associated accession codes are available at https://doi.org/10.1038/s41586-019-1320-2.

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**Author contributions** S.B. and J.M.F. conceived the ideas for the experiment and analysed the data. S.B. developed the theoretical model and performed the measurements. E.S.R. and S.B. fabricated the sample. S.B., E.S.R., M.P., M.W. and J.M.F. designed the microwave circuit and built the experimental setup. G.A. and M.W. performed finite-element method simulations. S.B. and D.P.L. developed the measurement software. S.B. and J.M.F. prepared the manuscript.

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**Additional information**

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resonators, and for the same gap sizes we extract $C_{\text{mod}} = (0.93, 0.95) \text{fF}$: Owing to the strong scaling of $g$, we expect $\Delta x \propto \frac{1}{1 + C}$, a reduction in the gap size as well as the circuit parasitic capacitance ($\beta \approx 0.3$ for the current device) would lead to substantial further improvement in coupling strength. Capacitor gaps as small as 30 nm have been demonstrated in a similar fabrication process using shadow-evaporated gold electrodes.

**System noise calibration.** We calibrate the system gain $G$ and system noise $n_{\text{add}}$ of both measurement channels by injecting a known amount of thermal noise using two temperature-controlled 50-Ω load. The calibrators are attached to the measurement setup with two 5-cm-long superconducting coaxial cables and a thin copper braid (for weak thermal anchoring to the mixing chamber plate) via two latching microwave switches (Radiall R573423600). By measuring the noise density (in square volts per hertz) at each temperature, as shown in Extended Data Fig. 2a, and fitting the obtained data with the expected scaling

$$N_i = \frac{1}{2} \coth \left( \frac{\hbar \omega_i}{2k_B T} \right) + n_{\text{add}}$$

we accurately calculate the gain ($G_1, G_2$) = (83.20(6), 79.99(88)) dB and the number of added noise photons ($n_{\text{add}}, n_{\text{add}}$) = (8.34(15), 11.5(27)) for each output. The 95% confidence-interval values are taken from the standard error of the shown fit.

**Quadrature histograms.** The generation of a two-mode squeezed thermal state can be verified intuitively in phase space by plotting the histograms representing the probability distribution of all possible combinations of the measured quadratures ($X_1, P_1, X_2, P_2$). We first measure the uncorrelated noise for each channel by performing a measurement with the microwave drives turned off. The result is shown in the insets of Extended Data Fig. 2a, indicating a thermal state with a variance corresponding to $n_{\text{add}} = 0.5$. In Extended Data Fig. 2b we plot the four relevant quadrature histograms obtained when the drive tones are turned on (Roehde and Schwarz SMA100B-B711 and SMI100A) and after subtraction of the previously measured histogram with the drives turned off. The single-mode distributions $[X_1, P_1]$ and $[X_2, P_2]$ are both slightly broadened, indicating a phase-independent increase in the voltage fluctuations, which shows that the output of each resonator is amplified. The same is true for the cross-mode distributions $[X_1, P_2]$ and $[X_2, P_1]$ at the chosen ideal rotation angle. The slight stretching in the direction of channel 2 is a result of the stronger red-detuned pump power in channel 2, which results in a higher output photon number (13.89) than that in channel 1 (12.83). In stark contrast, in the histograms showing the different outputs $[X_1, X_1]$ and $[P_1, P_1]$, the fluctuations increase along the one diagonal and decrease in the other, indicating a strong correlation between the two spatially separated modes.

**Device parameter calibration.** We use standard vector network analyser measurements to infer the resonator properties and, using the known system gain, the input attenuation. This calibrates the intra-cavity photon number which, together with the high-coercivity electromagnetically induced transparency measurements, yields the reported electromechanical coupling strengths $g_{\text{mod}}$ (ref. 34). We use dynamical back-action cooling$^{38}$ to infer the mechanical resonator damping rate $\gamma_{\text{mod}}$ and the mechanical phonon bath occupation $n_{\text{ph}}$. In Extended Data Fig. 3 we show the measured mechanical occupancy $n_{\text{mod}}$ versus the drive power $P_d$ of a red-detuned input tone obtained from the measured displacement noise on resonance with the two resonators$^{34}$. Both datasets follow closely the expected cooling model $n_{\text{mod}} = \frac{\pi}{8} (1 + C) + n_{\text{add}}$, and we obtain a mechanical resonator damping rate of $\gamma_{\text{mod}} / 2\pi = (4 \pm 2) \text{Hz}$ and a phonon bath occupation of $n_{\text{ph}} = 77$.

**Data availability**

The data that support the findings of this study are available from the corresponding authors on reasonable request.
**Extended Data Fig. 1 | Finite-element method simulations.**

**a,** Sample geometry. Important dimensions are indicated and the aluminium metallization is shown in yellow. **b,** Finite-element method simulated mechanical eigenfrequencies of the two fundamental in-plane nanobeam modes versus the tensile stress of the 65-nm-thick aluminium metallization. The insets show the displacement profile of the two modes. The dashed lines indicate the tensile stress corresponding to the two measured mechanical frequencies, $\omega_{m,1(2)}$. **c,** Simulated modulated capacitance of a single beam as a function of the capacitor gap size. The dashed lines indicate the capacitor gap sizes obtained from d, and the resulting modulated capacitances consistent with the measured resonance frequencies $\omega_{c,1(2)}$. The solid line shows a fit with $C_{\text{mod}} \propto x_0^{-0.6}$. **d,** Simulated electromechanical coupling strength between mechanical mode 1 at $\omega_{m,1}$ and the two measured microwave resonators at $\omega_{c,1(2)}$ as a function of the capacitor gap size. Dashed lines indicate the experimentally measured coupling strengths $g_{0,1(2)}$ and the two resulting capacitor gap sizes. Solid lines show fits with $g_0 \propto x_0^{-1.5}$. 

The dashed lines indicate the capacitor gap sizes obtained from d, and the resulting modulated capacitances consistent with the measured resonance frequencies $\omega_{c,1(2)}$. The solid line shows a fit with $C_{\text{mod}} \propto x_0^{-0.6}$. Simulated electromechanical coupling strength between mechanical mode 1 at $\omega_{m,1}$ and the two measured microwave resonators at $\omega_{c,1(2)}$ as a function of the capacitor gap size. Dashed lines indicate the experimentally measured coupling strengths $g_{0,1(2)}$ and the two resulting capacitor gap sizes. Solid lines show fits with $g_0 \propto x_0^{-1.5}$. 

Extended Data Fig. 2 | Quadrature measurements. a, System calibration of output channel 1 (top) and 2 (bottom). The measured noise density in units of quanta, \( S_i = (N_i/\zeta_i) - n_{\text{add},i} \), is shown as a function of the temperature \( T \) of the 50-\( \Omega \) load. The error bars indicate the standard deviation obtained from three measurements with 28,800 quadrature pairs each. The solid lines are fits to equation (5) in units of quanta, which yields the system gain and noise with the standard errors (95% confidence interval) stated in the main text. The insets show the phase space distribution with the pump tones turned off. These two-variable quadrature histograms are based on 604,800 measured quadrature pairs for each channel. b, Difference of the two-variable quadrature histograms with the pumps turned on and off for all quadrature-pair combinations in units of quanta (as calibrated in a), obtained using 216,000 pairs from both channels.
Extended Data Fig. 3 | Dynamical back-action cooling. Measured phonon occupation of the mechanical oscillator as a function of the red-detuned drive power $P_d$ at the input of microwave resonator 1 (blue) and 2 (red). From the fits (coloured lines) we infer a phonon bath occupation of $\bar{n}_m = 77$ and an intrinsic mechanical dissipation rate of $\gamma_m/2\pi = 4$ Hz.