Probing the quantum motion of a macroscopic mechanical oscillator with a radio-frequency superconducting qubit

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Long-lived mechanical resonators like drums oscillating at MHz frequencies and operating in the quantum regime offer a powerful platform for quantum technologies and tests of fundamental physics [1]. Yet, quantum control of such systems remains challenging, particularly owing to their low energy scale and the difficulty of achieving efficient coupling to other well-controlled quantum devices. Here, we demonstrate repeated, and high-fidelity interactions between a 4 MHz suspended silicon nitride membrane and a resonant superconducting heavy-fluxonium qubit [2-4], representing, to our knowledge, the first realization of resonant coupling in such a hybrid system at record-low frequencies. The qubit is initialized at an effective temperature of 21 μK and read out with 77% single-shot fidelity. During the 6 ms lifetime of the membrane the two systems swap excitations more than 300 times. After each interaction, a state-selective detection is performed, implementing a stroboscopic series of weak measurements that provide information about the mechanical state. The accumulated records reconstruct the position noise-spectrum of the membrane, revealing both its thermal occupation $n_{th} \approx 47$ at 10 mK and the qubit-induced back-action. By preparing the qubit either in its ground or excited state before each interaction, we observe an imbalance between the emission and absorption spectra, proportional to n_{th} and $n_{th}+1$ respectively, a hallmark of the non-commutation of phonon creation and annihilation operators. Since the predicted Diósi–Penrose gravitational collapse time [5-6] is comparable to the measured mechanical decoherence time, our architecture enters a regime where gravity-induced decoherence could be tested directly [7].

References

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Figures

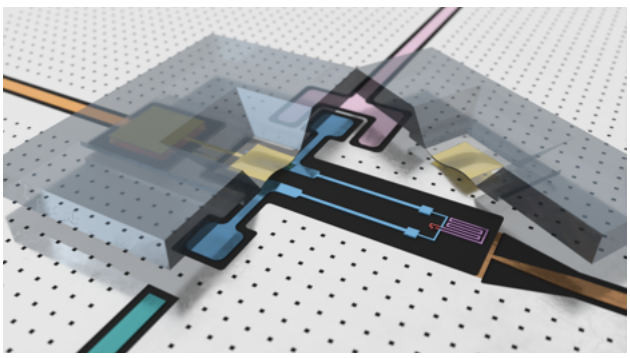

Figure 1: 3D schematic of the mechanical–fluxonium device: an Al-metallized suspended SiN membrane (yellow, cutaway) sits above the fluxonium electrodes (blue), forming a vacuum-gap capacitor; the remaining colored regions depict the fluxonium chip.