Quantum ground state and single-phonon control of a mechanical resonator

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Overview

- quantum mode is cooled to its ground state (using a mechanical oscillator)

- coupling of the mechanical resonator to a qubit

- creation of single quantum excitations in the resonator

- quantum mechanics applies to macroscopic mechanical objects
**Challenge:**

- goal: use of a mechanical system to demonstrate QM

- approaches: measuring a single mechanical resonance

- but: cooling a mechanical resonance to its quantum ground state requires: $T < \frac{\hbar f}{k_B}$
  $\rightarrow f = 1 \text{ kHz} \rightarrow T < < 50 \text{nK}$

*O`Connell et al.:*

resonator with an isolated mechanical mode near 6 GHz
$\rightarrow 0.1 \text{K}$ are enough to reach ground state
resonator measurement via superconducting qubit

suspended film bulk acoustic resonator made of piezo Al / AlN / Al

classical transmission of a mechanical resonator

\[ f_s = \frac{1}{2} \pi (L_mC_m)^{1/2} \approx 6.07\text{GHz} \]

\[ f_r = \frac{1}{2} \pi (L_mC_S)^{1/2} \approx 6.10\text{GHz} \]
**Qubit spectroscopy**

\[ \Delta E = E_e - E_g \]
\[ f_q = \frac{\Delta E}{h} \]
\[ 5 \text{ GHz} < f_q < 10 \text{ GHz} \]

\[ \Omega = \frac{2g}{h} = 124 \text{ MHz} \]
microwaves coupled to resonator via $C_x$ instead through qubit

- mechanical resonator $\equiv$ narrow band pass filter
  $\rightarrow$ qubit excitation only near $f_r$

- additional feature for high flux bias
  $\rightarrow$ qubit state ejection due to highly excited resonator
so far classical measurements

now: using the qubit to probe the energy state of the resonator without microwave signal applied

qubit = quantum thermometer

1) prepare qubit in $|g\rangle$

2) flux bias to place qubit within $\Delta = f_q - f_r$ for 1$\mu$s

3) take qubit out of $\Delta$ and measure $P_e$

$\rightarrow$ qubit remains in $|g\rangle$ for all $\Delta$

$\rightarrow$ $\langle n \rangle \ll 1$

$\rightarrow$ resonator is in its ground state
**quantum excitations – entangled qubit-resonator quantum state**

**a**

- Mechanical resonator
- Qubit
- Meas.

**b**

- Qubit excitation is exchanged with a phonon in the resonator

minima: transfer of the excitation from the qubit to the resonator

maxima: return of excitation from the resonator to the qubit
Resonator energy relaxation time

injecting a single phonon into the resonator and measuring its decay

→ \( T_{1r} \approx 6.1 \) ns

Resonator dephasing time

→ \( T_{2r} \approx 20 \) ns > 2\( T_{1r} \)

(complicated exp with high error probability)
**bosonic nature of the resonator:**

1) microwave excitation of resonator while qubit out of resonance

MW amplitude varies

2) qubit in resonance for a time \( \tau \)

3) \( P_e \) in dependence of MW amplitude and interaction time

→ increasing frequency in \( P_e \) oscillations with increasing MW frequency

swap frequency between qubit and resonator \( \sim (\langle n \rangle)^{1/2} \)

→ bosonic
**Conclusion**

- mechanical resonator is cooled to its ground state

- coupling of the mechanical resonator to a qubit

- creation of single quantum excitations in the resonator

- creation of entanglement between resonator and qubit

- quantum mechanics applies to macroscopic mechanical objects