Advanced Workshop on Nanomechanics

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Noise-Resilient Quantum Information Protocols in An Optomechanical Quantum Interface

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Noise-Resilient Quantum Information Protocols in An Optomechanical Quantum Interface

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COINS
1. What are mechanical systems useful for?  
   -- connect hybrid systems/different channels/noise

2. Optomechanical quantum interface  
   -- quantum operations/protocols  
   -- Overcome mechanical noise via dark modes

3. Another mechanical mode coupling with superconducting resonator

4. Emulating phonons …
What Are Mechanical Systems Useful For?

- Theory & exp advancements in mechanical system
- Quantum state engineering
- Ground state cooling
- Squeezing
- Material/sample engineering
  - Q-factor 10,000,000...
  - Freq. range
  - Coupling Strong Ultra-strong...

Any applications besides studying quantum features of macroscopic systems?
Mechanical systems can couple with numerous other systems

- Coupling with qubits, cavity modes, spins in solids etc…
- Coupling with systems in different frequency range – microwave – optical…
- Coupling with systems in different setup – atomic systems, solid-state, …
- Weak coupling, strong coupling, ultra-strong coupling (?) …

Cooper pair box
Qubit-resonator coupling
Armour, Blencowe, Schwab, PRL (2002)

Cavity-mechanical mode
Different frequency range
What Are Mechanical Systems Useful For?

The mechanical systems can be exploited as an interface to connect systems with very different frequency or property:

- Connecting qubits as a quantum bus
- Connecting qubit with cavity
- Connecting optical cavities at different frequency
- Connecting optical cavity and microwave cavity
- Connecting solid-state device and atomic systems …

Cavity optomechanics – Aspelmeyer, Kippenberg, Marquardt, arxiv:1303.0733

- Strong coupling between light and mechanical modes demonstrated (in both microwave and optical systems, $g/\kappa > 1$)
- Mechanical modes approach quantum ground state


- Optomechanically induced transparency, mechanical dark mode, etc

- Strong/controllable light-matter coupling/large cooperativity
- Mechanical mode connects cavities with different frequencies
e.g. optical cavity – mechanical mode - microwave cavity

- Connect different parts of a hybrid quantum network/transducer
- Achieve quantum operations through mechanical mode
Two cavity modes (information carrier) and a mechanical mode (interface). Cavity modes can have distinct frequency – microwave, optical … (hybrid). Input, output channels for all three modes – mechanical thermal noise.

Goal: manipulate quantum states in the cavity channels/modes using their coupling with the mechanical mode.

- Transfer of quantum states – quantum wavelength conversion
- Generate entanglement between cavity modes of different frequencies
Mechanical Effects of Light

Radiation pressure force on the mirror – cavity backaction

\[ H_{int} = G_0 a^\dagger a \hat{x} = F \cdot \hat{x} = \hbar \Delta \omega \cdot a^\dagger a \]

e.g. C.K. Law, PRA (1995), Interaction between a moving mirror and radiation pressure: A Hamiltonian formulation
Mechanical Effects of Light

Radiation pressure force and effective linear coupling

Cavity-mechanical mode coupling: mechanical shift of cavity resonance

\[ H_G = -G_i a_i^\dagger a_i q \]

Pumping on cavity mode – steady state amplitude, \( \Delta_i \): laser detuning

\[ a_{i,s} = \frac{-i E_i}{\kappa_i/2 - i(\Delta_i + G_i q_s)} \]

Red sideband driving – effective linear coupling

\[ H_{eff} = \epsilon_i a_i^\dagger b_m + \epsilon_i^* b_m^\dagger a_i \]

Blue sideband driving – effective linear coupling (instability etc…)

\[ H_{eff} = i\epsilon_i \left( a_i^\dagger b_m^\dagger - b_m a_i \right) \]
Mechanical Effects of Light

Radiation pressure force and effective linear coupling

**Anti-Stokes**

Cavity resonance

Converst phonons to photons.

Red detuned driving

**Stokes**

Cavity resonance

Similar to parametric down conversion.

Blue detuned driving
Simple quantum wave length conversion scheme

Red sideband driving – beam-splitter operation

\[ H_{eff} = \epsilon_i a_i^\dagger b_m + \epsilon_i^* b_m^\dagger a_i \]

Generate transformation - transfer of state with two swap pulses \( \epsilon_i t = \pi/2 \)

\[
\begin{align*}
    a_i(t) &= \cos(\epsilon_i t)a_i(0) + i \sin(\epsilon_i t)b_m(0) \\
    b_m(t) &= \cos(\epsilon_i t)b_m(0) + i \sin(\epsilon_i t)a_i(0)
\end{align*}
\]

Double-swap scheme:
1. Swap modes \( a_1 \) and \( b_m \) - initial state to \( b_m \)
2. Swap modes \( b_m \) and \( a_2 \) - initial state to \( a_2 \)
Simple quantum wave length conversion scheme

- Swapping via mechanical mode, thermal noise degrades conversion fidelity
- Cavity damping degrades conversion fidelity
- Fidelity for gaussian states reduces as:
  \[-\gamma_m T (2n_{th} + 1) \cosh(2r)/4\]
  
  \(T = \) time of operation, \(n_{th} = \) thermal number

Pre-cooling pulse ‘1’: swap \(a_1\) (ground state) and \(b_m\) (thermal state)

Transient cooling: partially remove thermal noise, improve state transfer

Tian, Wang, PRA 82, 053806 (2010)
Simple entanglement generation

**Blue sideband driving – parametric amplification**

\[ H_{eff} = i\epsilon_i \left( a_i^\dagger b_m^\dagger - b_m a_i \right) \]

Generate two-mode squeezing – between cavity and mechanical mode

\[
\begin{align*}
    a_i(t) &= \cosh(\epsilon_i t) a_i(0) + i \sinh(\epsilon_i t) b_m^\dagger(0) \\
    b_m(t) &= \cosh(\epsilon_i t) b_m(0) + i \sinh(\epsilon_i t) a_i^\dagger(0)
\end{align*}
\]

Combine this with swap pulse between other cavity and mechanical mode

Continuous variable entanglement between cavities

- Also subject to mechanical noise
- Noise propagates to all modes after two pulses
- Stability issue
- …
Simple entanglement generation

Previous work: design parametrically coupled mechanical/electrical resonators for two-mode squeezing, then squeezing

Generate parametric amplifier interaction, followed by beam-splitter operation

Can be extended to two cavity entanglement by swap gate on mechanical mode and 2nd cavity

Tian, Allman, Simmonds, NJP 10, 115001 (2008)
Previous work

**Various approaches and system setups: (photons, photon-phonon)**

**Potential issues:**
- Instability under the blue-detuned drive and nonlinearity
- Entanglement/couplings constrained by stability conditions
- Thermal noise in mechanical mode

**Why want entanglement:**
- Key resource for quantum network, quantum teleportation …
- Quantum feature in macroscopic system, quantum-classical boundary
- Hybrid quantum systems: bridging very different frequency scales
Overcome Mechanical Noise?!

![Diagram](image-url)
Optomechanical Quantum Interface

- For simplicity, detunings in resonance with mechanical frequency
- Simultaneous driving on two cavities

Red-detuned – Red-detuned
- quantum wavelength conversion
- discrete state entanglement

Red-detuned – Blue-detuned
- continuous variable entanglement
Red-Red detuned driving – Mechanical dark mode

\[ H = \sum_{i=1,2} -\hbar \Delta_i a_i^{\dagger} a_i + \hbar g_i (a_i^{\dagger} b_m + b_m^{\dagger} a_i) + \hbar \omega_m b_m^{\dagger} b_m \]

Mechanical dark mode

\[ \psi_1 = (-g_2 a_1 + g_1 a_2)/g_0 \]

Dark mode energy separated from other modes

\[ g_0 = \sqrt{g_1^2 + g_2^2} \]

\[ \lambda_1 = 0, \; \lambda_{2,3} = \pm \sqrt{g_1^2 + g_2^2} \]

Remains in dark mode when adjusting coupling \( g_{1,2} \) adiabatically (Landau-Zener condition)

\[ |d g_i / dt| / g_0 \ll g_0 \]
Adiabatic quantum wave length conversion of cavity state

\[
\psi_1 = \left(-g_2 a_1 + g_1 a_2 \right)/g_0
\]

time \( t=0 \), \( g_1=0 \), \( g_2=-g_0 \), dark mode \( a_1(0) \)
time \( t=T \), \( g_1=g_0 \), \( g_2=0 \), dark mode \( a_2(T) \)
Initial state in mode \( a_1 \) is transferred to mode \( a_2 \)

Finite damping, solve Langevin equation

\[
\frac{id\vec{v}(t)}{dt} = M(t)\vec{v}(t) + i\sqrt{K}\vec{v}_{in}(t)
\]

\[
\vec{v}(t) = [a_1, b_m, a_2]^T
\]

Not totally dark!
Adiabatic quantum wave length conversion of cavity state

Fidelity for gaussian states at time $T$: $F = F_1 F_2$

$F_1 \approx 1 - f(0, T)(\cosh(2r) - 1) - f_s \cosh(2r)$ \hspace{1cm} $f(0, T) \sim (\kappa_1 + \kappa_2)T/4$

$F_2 \approx 1 - f^2(0, T)y(\alpha)/2.$ \hspace{1cm} $f_s \lesssim \gamma_m(2n_{th} + 1)T((\kappa_1 - \kappa_2)/4g_0)^2$

$F_1$, linear vs $\kappa_1$, $F_2$, quadratic vs $\kappa_1$

Effect of mechanical noise reduces by significant ratio

Special case of $\kappa_1 = \kappa_2$: mechanical noise cancals

$\delta F = F(0) - F(\gamma_m)$ at $\kappa_2=0$,  
(effect of mechanical noise)

Increases quadraticly with $\kappa_1$  
Larger for finite squeezing $r$

L. Tian, PRL 108, 153604 (2012). See also  
High-fidelity swapping of cavity state

Could we achieve a two-way process for exchange of states?
- State from a1 to a2
  \[ a_2(T) = a_1(0) \]
- State from a2 to a1
  \[ a_1(T) = a_2(0) \]

How to? --- Destructive interference to cancel mechanical components

Condition: \( \frac{\lambda}{g_0} \approx \frac{1}{2n} \). Numerical results for \( n=2 \):

Initial states: \( a_1 = \) coherent state \( \alpha=1 \), \( a_2 = \) vacuum; two curves \( n_{th}=0, 100 \);

Target states: \( a_1 = \) vacuum, \( a_2 = \) coherent state \( \alpha=1 \)
Time window: 5 – 10 nsec.

More details see S. Huang & L. Tian, coming soon …
High-fidelity pulse transmission with impedance matching

Input $a_{1\text{ in}}(t)$ transferred to output $a_{2\text{ out}}(t)$
Noise operators $a_{2\text{ in}}(t)$ and $b_{\text{in}}(t)$

Langevin equation in frequency space
Input-output relation
Transmission matrix – unitary operator

$$\tilde{v}_{\text{out}}(\omega) = \hat{T}(\omega)\tilde{v}_{\text{in}}(\omega)$$

Output operator
$$a_{\text{out}}^2(\omega) = \hat{T}_{31}(\omega)a_{\text{in}}^1(\omega) + \hat{T}_{32}(\omega)b_{\text{in}}(\omega) + \hat{T}_{33}(\omega)a_{\text{in}}^2(\omega)$$

Condition for high fidelity
$$\hat{T}_{31}(\omega) \rightarrow 1 \quad \hat{T}_{32}(\omega), \hat{T}_{33}(\omega) \rightarrow 0$$
High-fidelity pulse transmission with impedance matching

- **Optimal transmission condition:** impedance matching \( \hat{T}_{31}(\omega) \to 1 \)
- Half width \( \sim \) cavity bandwidth, \( \Delta \omega \sim \kappa_i \)
- Fidelity drops with input pulse spectral width \( \sigma_\omega \quad \sigma_\omega \ll \Delta \omega \)

L. Tian, PRL 108, 153604 (2012). See also
Coherent optical wavelength conversion via cavity optomechanics

Jeff T. Hill\textsuperscript{1,\*}, Amir H. Safavi-Naeini\textsuperscript{1,\*}, Jasper Chan\textsuperscript{1} & Oskar Painter\textsuperscript{1}


Optomechanical Dark Mode

Chunhua Dong, Victor Fiore, Mark C. Kuzyk, Hailin Wang\textsuperscript{*}

Science (2013)

Coherent state transfer between itinerant microwave fields and a mechanical oscillator

T. A. Palomaki\textsuperscript{1,2}, J. W. Harlow\textsuperscript{1,2}, J. D. Teufel\textsuperscript{3}, R. W. Simmonds\textsuperscript{3} & K. W. Lehnert\textsuperscript{1,2}

Nature (2013)

UCSB work, see talk by Andrew Cleland, Monday
Red-Blue detuned driving – Bogoliubov dark mode

\[ H_I = \hbar g_1 (a_1^\dagger b_m + b_m^\dagger a_1) + i\hbar g_2 (a_2^\dagger b_m^\dagger - a_2 b_m) \]

1. Coupling diagram, energy spectrum

One “dark” mode and two bright modes separated by energy \( g_0 \)

\[ g_0 = \sqrt{g_1^2 - g_2^2} \]

Eigenmodes

\[
\begin{array}{c|c|c}
  g_0 & \alpha_2 \\
  0 & \alpha_1 \\
 -g_0 & \alpha_3 \\
\end{array}
\]

2. Stability condition
   (strong coupling regime)

\[ \frac{g_1^2}{g_2^2} > \max \left\{ \frac{\kappa_2}{\kappa_1}, \frac{\kappa_1}{\kappa_2} \right\} \]

\[ g_1 = g_0 \cosh(r) \quad g_2 = g_0 \sinh(r) \]
Red-Blue detuned driving – Bogoliubov dark mode

1. “Dark” mode, $\lambda_1=0$ 
   $$\alpha_1 = -i \sinh(r) a_1 + \cosh(r) a_2^\dagger$$

2. Two bright modes 
   $\lambda_{2,3} = \pm g_0$
   $$\alpha_{2,3} = \frac{1}{\sqrt{2}} \left( \cosh(r) a_1 \pm b_m + i \sinh(r) a_2^\dagger \right)$$

3. Bogoliubov modes
   Two modes under parametric amplifier coupling 
   $$H_s = -g_s \left( a_1 a_2 + a_1^\dagger a_2^\dagger \right)$$
   System operators evolve in terms of Bogoliubov modes 
   $$r = g_s t$$
   $$a_1(t) = \beta_1(r) = \cosh(r) a_1 + i \sinh(r) a_2^\dagger$$
   $$a_2(t) = \beta_2(r) = \cosh(r) a_2 + i \sinh(r) a_1^\dagger$$

4. Relation to eigenmodes
   $$\alpha_1 = \beta_2^\dagger; \ (\alpha_2 + \alpha_3)/\sqrt{2} = \beta_1$$

5. finite damping
   (eigenvalues modified too)
   $$-i\delta \lambda_i$$
   $$\alpha_1 = \beta_2^\dagger + x_1 b_m; \ (\alpha_2 + \alpha_3)/\sqrt{2} = \beta_1 - \sqrt{2} x_3 b_m$$
Robust Entanglement Generation

Central idea

• Entanglement generated via mechanical mode – effect of noise

• Excitation of dark mode doesn’t involve mechanical mode => $\beta_2(r)$

• Excitation of bright modes mix cavity and mechanical modes

• Quantum interference cancels mechanical modes => $\beta_1(r)$

• Cavity/cavity output operators have forms of Bogoliubov operators to leading order, mechanical noise suppressed
Entanglement in cavity state in time domain

Solve Langevin equation in time domain for operator evolution

Dark mode; bright modes with phase factors including mechanical component

\[ \alpha_1(t) = \alpha_1(0); \alpha_{2,3}(t) = \exp(\mp i\varphi(t))\alpha_{2,3}(0) \]

Bogoliubov modes for cavity at time \( t \)

\[ \beta_2(t) = \beta_2(0) \]

\[ \beta_1(t) = \beta_1(0) \cos \varphi(t) - i b_m(0) \sin \varphi(t) \]

Cavity at time \( t \) includes \( b_m(0) \)

Choose time \( t_n \) to cancel mechanical component,

\[ \varphi(t_n) = n\pi \]

At \( t_n \),

\[ g_1 = g_0 \cosh(r) \quad g_2 = g_0 \sinh(r) \]

Couplings can have many choices of time dependence

\[
\begin{pmatrix}
    a_1(t) \\
    a_2^\dagger(t)
\end{pmatrix}
= \begin{pmatrix}
    \cosh(r) & -i \sinh(r) \\
    i \sinh(r) & \cosh(r)
\end{pmatrix} \begin{pmatrix}
    \cosh(r_0)(-1)^n & i \sinh(r_0)(-1)^n \\
    -i \sinh(r_0) & \cosh(r_0)
\end{pmatrix} \begin{pmatrix}
    a_1(0) \\
    a_2^\dagger(0)
\end{pmatrix}
\]
Entanglement in cavity state in time domain

Solving Langevin equation at finite damping rates
Cavity at time $t_n$

\[
a_1(t_n) = \left[ (-1)^n \cosh(r)a_1(0) - i \sinh(r)a_2^\dagger(0) \right] + f_1(a_1(0), a_2^\dagger(0)) + y_1 b_m(0) + \text{noise integral}
\]
\[
a_2^\dagger(t_n) = \left[ i(-1)^n \sinh(r)a_1(0) + \cosh(r)a_2^\dagger(0) \right] + f_2(a_1(0), a_2^\dagger(0)) + y_2 b_m(0) + \text{noise integral}
\]

Effect of initial mechanical noise is eliminated to leading order!

- **Ideal terms zero damping**
  - *Eigenmode damping* $O(\kappa_i/g_0)$
  - *Bath fluctuations* $O(\gamma_m/g_0)n_{th}$

- *First-order mixing with mechanical mode*
  \[O(\kappa_i^2/g_0^2)n_0\]

Distinguish thermal number of initial state $n_0$ and of bath $n_{th}$

Couplings are $g_1(t) = g_0 \cosh(\lambda t)$ and $g_2(t) = g_0 \sinh(\lambda t)$
Entanglement in cavity state in time domain

Numerical simulation of time evolution with \( r(t_2) = 1 \)
Peaks appear for finite thermal number at \( t_n = n\pi/g_0 \)
- Peak height slowly varies with \( n_{\text{th}} \)
- Peak width depends on \( n_0 \)

\[ n_0 = n_{\text{th}} = 0, 10, 100, 1000 \]

\[ g_1(t) = g_0 \cosh(\lambda t) \] and \[ g_2(t) = g_0 \sinh(\lambda t) \]

\[ \kappa_0/g_0 = 0.1 \]
\[ \gamma_m/g_0 = 0.0003 \]
Entanglement at selected peak values

- solid: constant coupling $r = 1$
- dashed: adiabatic increase of coupling $r(t_2) = 1$
- dotted: stationary scheme

Sizable entanglement at large $n_{th}$

L. Tian, PRL 110, 233602 (2013)
Entanglement in cavity output in frequency domain

Operators in input and output – x = in, out – g: profile function

\[ a^{(i)}_x(\omega_n) = \int d\omega g(\omega - \omega_n) a^{(i)}_x(\omega) \]

Eigenmode excitation at given frequency, crucial for the effect

\[ \tilde{\alpha}(\omega_n) = i(I\omega_n - \Lambda)^{-1} U^T \sqrt{\kappa} v_{in}(\omega_n) \]

Strong excitation when \( \omega_n \) near eigenvalues
At \( \omega_n = 0 \), dark mode strongly excited \( \sim 1/\delta\lambda_1 \),
  bright modes weakly excited \( \sim 1/g_0 \)

At \( \omega_n = g_0 \), one bright mode strongly excited \( 1/\delta\lambda_2 \), (similarly at \( -g_0 \))
  dark mode weakly excited \( \sim 1/g_0 \)
  other bright mode weakly excited \( \sim 1/2g_0 \)

Entanglement can be strong at these frequencies
Entanglement in cavity output in frequency domain

Top panels:
$(\kappa_1, \kappa_2) = (0.3, 0.2)$

Bottom panels:
$(\kappa_1, \kappa_2) = (0.2, 0.3)$

Dependence on damping rates due to effect on $\delta \lambda_i$

$n_{th} = 0, 10, 100, 1000$

Strong entanglement at $0, g_0, -g_0$

At $0$, strong & robust
Side peaks, strong & non-robust

See results in Barzanjeh et al, PRL 109, 130503 (2012)
“Reversible Optical-to-Microwave Quantum Interface”
Entanglement in cavity output in frequency domain

At $\omega_n=0$, dark mode strongly excited $\sim 1/\delta \lambda_1$, $\alpha_1 \approx \beta_2^\dagger$

$$\alpha_1(\omega_0) = \left( \frac{\sinh(r)}{\delta \lambda_1} \frac{i x_1}{\delta \lambda_1} \frac{i \cosh(r)}{\delta \lambda_1} \right) \cdot \sqrt{K} \vec{v}_{in}(\omega_0)$$

Bright modes weakly excited $\sim 1/g_0$

$$\alpha_{2,3}(\omega_0) = \left( \mp \frac{\cosh(r)}{\sqrt{2}g_0} - \frac{1}{\sqrt{2}g_0} \mp \frac{i \sinh(r)}{\sqrt{2}g_0} \right) \cdot \sqrt{K} \vec{v}_{in}(\omega_0)$$

Symmetry in bright modes gives

$$\beta_1(\omega_0) \approx (\alpha_2(\omega_0) + \alpha_3(\omega_0))/\sqrt{2} = -\sqrt{\gamma_m b_{in}(\omega_0)}/g_0$$

Again, in cavity modes, mechanical input $\sim 1/g_0$; cavity inputs $\sim 1/\delta \lambda_1$

At $\omega_n=g_0$, one bright mode strongly excited $1/\delta \lambda_2$, (similarly at $-g_0$)

dark mode weakly excited $\sim 1/g_0$

other bright mode weakly excited $\sim 1/2g_0$

L. Tian, PRL 110, 233602 (2013)
Optomechanical quantum interface connects quantum states in different cavities – facilitate scalable quantum systems.

- High fidelity quantum wave length conversion via dark mode.
- Robust entanglement generation via excitation of dark mode and quantum interference of the mechanical mode.
Trapped Particle and Superconducting Circuits

- Hybrid system connects trapped particle and superconducting circuits
- Trapped motion: 10 – 500 MHz, Superconducting resonator: 10 GHz
- Parametric coupling that converts resonator state to motion state

Previous work: Heinzen and Wineland PRA (1990), Kielpinski et al PRL (2012)

Circuit approach and challenges – our initial thoughts

Excess circuit noise kills quantum signal on pickup electrodes
Solution – driven electron motion in nonlinear potential, classical motion becomes the parametric source

\[ U_{\text{eff}} = gx^2 \dot{\varphi} \]

\[ x_i = A_d \cos(\Omega_d t) + \hat{x}_i \]

Trapped Particle and Superconducting Circuits

- Effective coupling: beam-splitter operation, parametric amplifier operation

\[ H_{er} = \hbar g \cos(\Omega_d t) \left( e^{i(\Omega - \omega_y)t} a_\phi^+ a_y + e^{i(\Omega + \omega_y)t} a_\phi^+ a_y^+ + h.c. \right) \]

Applications
Transfer electron motion with superconducting LC oscillators or other electrons

Electron-transmon coupling – with 3D transmon (long decoherence time)

Electron spin-motion conversion – similar to ion trap
Architecture for large scale quantum computer …
Emulating Phonons with Circuit QED

Electron-phonon interaction – fundamental effect in condensed matter
BCS – electron pairing via phonons, Peierls instability and Jahn-Teller effect
Small polaron formation: lattice distortion in small regime
L.D. Landau (1933) …
Features: larger effective mass, lattice distortion, anomalous fluctuations
Holstein model for local electron-phonon interaction, molecular crystals … (vs SSH model)
Coupled fermionic and bosonic degrees of freedom
Can’t be exactly solved or numerically calculated, simple system with interesting many-body physics

\[ H = \hbar \omega \sum_i a_i^+ a_i - t \sum_{<i,j>} c_i^+ c_j + \hbar g \sum_i c_i^+ c_i (a_i^+ + a_i) \]
Emulating Phonons with Circuit QED

- Transmon qubit emulates electrons
- CPW resonator emulates optical phonons
- Tunable coupling (electron hopping) via SQUID loop
- Jordan-Wigner transformation on qubit spins
Emulating Phonons with Circuit QED

\[ H = \hbar \omega \sum_i a_i^+ a_i - t \sum_{<i,j>} c_i^+ c_j + \hbar g \sum_i c_i^+ c_i (a_i^+ + a_i) \]

Parameter regimes: \( g/\omega > 1 \) (strong coupling) \( t/\omega > 1 \) (adiabatic)
Small polaron formation \( \lambda = g^2/\omega t > 1 \)

Advantage of system:
Can access all regimes of interest (adiabatic, anti-adiabatic, …)
Real nearest neighbor coupling, dispersionless phonons
We developed generic scheme for the preparing of polaron excitations by exploring translational symmetry – using pulses

\[ \Omega(q) = \frac{\hbar g(t)}{\sqrt{N}} \sum_n (\sigma_n^+ e^{-iqn} + \sigma_n^- e^{iqn}) \]

Previous work:
Stojanovic, Shi, Bruder, Cirac, PRL 109, 250501 (2012) ion trap systems
Mezzacapo et al, PRL 109, 200501 (2012) digital quantum simulation
Also, works on polar molecules, Rydberg atoms
How to calculate? – use Toyozawa-type variational Ansatz to test system behavior

\[ \tilde{N}_{ph} = \langle \tilde{\psi}_{\kappa=0} | \sum_i a_i^\dagger a_i | \tilde{\psi}_{\kappa=0} \rangle \]

Phonon number

Variance of resonators based on measurement of qubit flip

Squeezing 1.25 dB

\[ g_H = g/\omega \propto \epsilon \]
\[ t/2\pi = 80 \text{ MHz} \]

Mei, Stojanovic, Siddiqi, Tian, arXiv:1307.0906
Emulating Phonons with Circuit QED

- Circuit QED gives a tunable platform to emulate e-ph physics in the Holstein model in all interesting parameter regimes, without the restriction of phonon dispersion and long-range coupling.
- We develop a state preparation scheme which can be applied to other systems.
- Squeezing in resonator can be generated during small polaron formation.
Optomechanical quantum interface:
Group members: Dan Hu (graduate student), Sumei Huang (postdoc)
Collaborators: Hailin Wang and group (U Oregon)

Trapped electron – resonator hybrid system
Collaborators: Hartmut Haeffner, Nikos Daniilidis, Dylan Gorman (Berkeley)

Emulator for electron-phonon physics
Group member: Feng Mei (postdoc)
Collaborators: Vladimir Stojanovic (U Basel), Irfan Siddiqi (Berkeley)

Acknowledgement
Strong coupling between light and mechanical modes

\[ \omega_m/2\pi, 10 \text{ MHz} \quad \kappa/2\pi, 100 \text{ kHz} \quad g/2\pi, 1 \text{ MHz} \]

\[ \omega_m/2\pi, 100 \text{ MHz} \quad \kappa/2\pi, 7 \text{ MHz} \quad g/2\pi, 10 \text{ MHz} \]
Quantum Wavelength Conversion

Adiabatic scheme via mechanical dark mode

Langevin eq. in interaction picture

\[ \frac{d\vec{v}(t)}{dt} = M(t)\vec{v}(t) + i\sqrt{K}\vec{v}_{in}(t) \]

\[ \vec{v}(t) = [a_1, b_m, a_2]^T \]

\[ M(t) = \begin{pmatrix} -i\frac{\kappa_1}{2} & g_1(t) & 0 \\ g_1(t) & -i\frac{\gamma_m}{2} & g_2(t) \\ 0 & g_2(t) & -i\frac{\kappa_2}{2} \end{pmatrix} \]

Finite damping: we treat damping terms in M(t) as perturbation terms

Dark mode contains small contribution from mechanical mode

\[ \psi_1 = \left( -\frac{g_2}{g_0}a_1 - \frac{i(\kappa_1 - \kappa_2)g_1g_2}{2g_0^3}b_m + \frac{g_1}{g_0}a_2 \right) \text{ Not totally dark!} \]

Eigenenergy is modified – causes damping

\[ \lambda_1 = -i \left( \frac{g_1^2}{2g_0^2}\kappa_2 + \frac{g_2^2}{2g_0^2}\kappa_1 \right) \]

Hence, adiabatic conversion can be affected by mechanical noise

How to characterize these effects?
Simple entanglement generation

PHYSICAL REVIEW B 74, 125314 (2006)

Scheme for quantum teleportation between nanomechanical modes

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We study a quantum teleportation scheme between two nanomechanical modes without local interaction. The nanomechanical modes are linearly coupled to and connected by the continuous variable modes of a superconducting circuit consisting of a transmission line and Josephson junctions. We calculate the fidelity of transferring Gaussian states at finite temperature and nonunit detector efficiency. For coherent states, a fidelity above the classical limit of 1/2 can be achieved for a large range of parameters.