Optomechanical micro-macro entanglement

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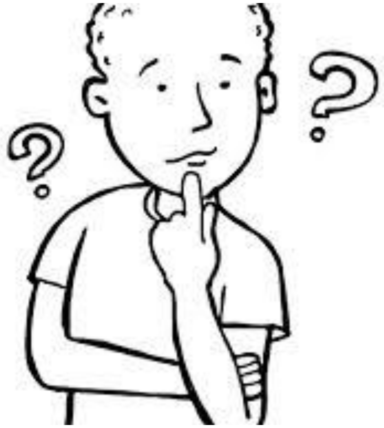
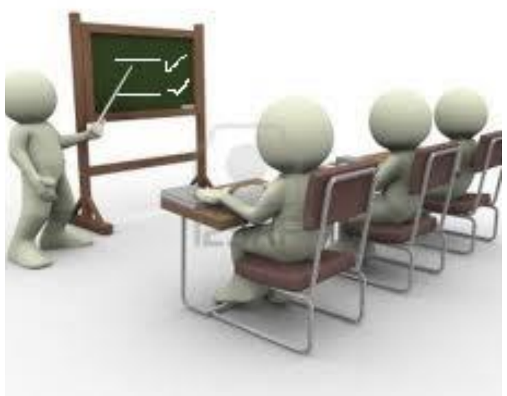
Background and Motivation

Possible way out



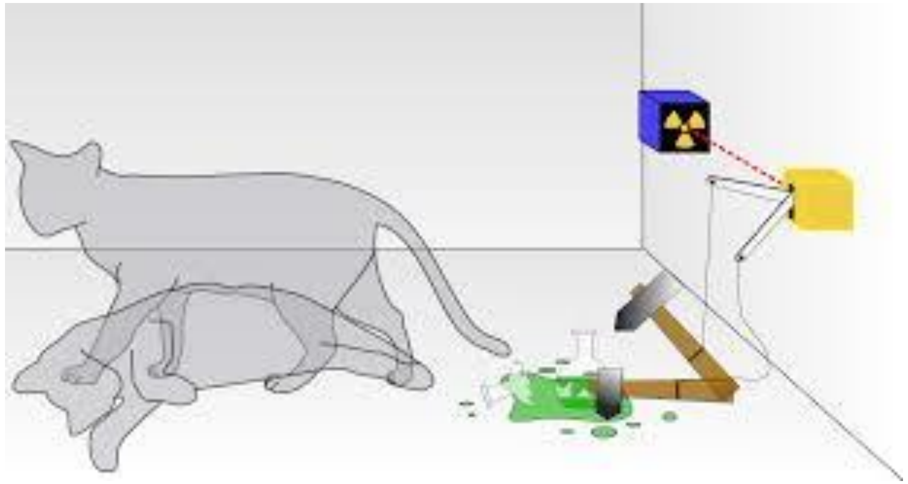
An idea

Summary



Background and Motivation

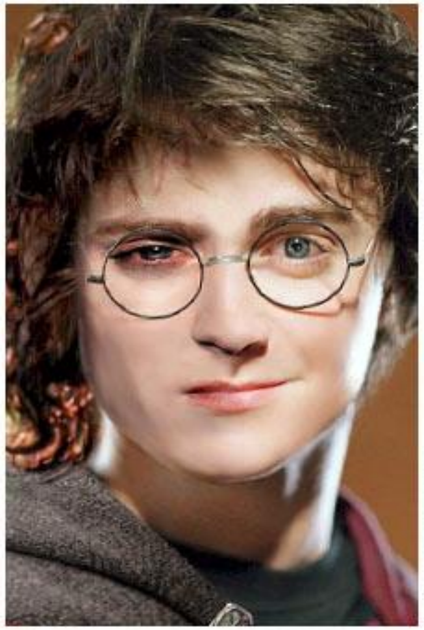
Schrödinger's thought experiment



- *Classical picture* → Open the box → see the cat dead or alive.
- *Quantum picture* → Simultaneous perception of a live and a dead cat. Is it possible?

$$\frac{1}{\sqrt{2}}(|\phi_{NO-decay}\rangle|\psi_{ALIVE-cat}\rangle + |\phi_{YES-decay}\rangle|\psi_{DEAD-cat}\rangle)$$

Possible way out



Elijah Wood and Daniel Radcliffe

Hillary and Bill Clinton

- A pertinent question:" How can we demonstrate macroscopic superposition and micro-macro entanglement?"

Possible way out

!!!!PHOTONS!!!!

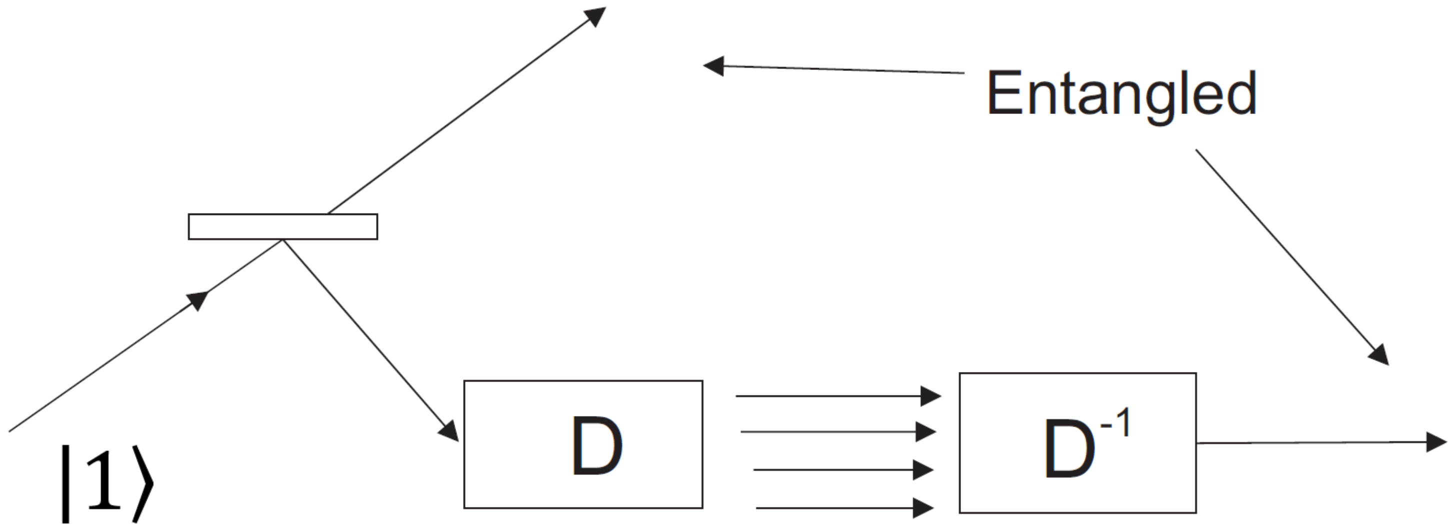
- Microscopic state → single photon level
- Macroscopic state → millions or hundreds of millions of photons

So, why not amplify the microscopic quantum state. But?

- Problem → It is very hard to detect and characterize such a state as the measurements need to have extremely high resolution.
- Solution → By local operations, convert the macroscopic state back to microscopic state to demonstrate entanglement.

Scheme

Amplification by displacement



Entanglement at the end proves micro-macro entanglement in the intermediate step.

Micro-macro correlations

- Delocalized single-photon state

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle_A \otimes |1\rangle_B + |1\rangle_A \otimes |0\rangle_B\right)$$

- After displacement

$$|\psi_D\rangle = \frac{1}{\sqrt{2}}\left(|0\rangle_A \otimes \hat{D}(\alpha)\,|1\rangle_B + |1\rangle_A \otimes \hat{D}(\alpha)\,|0\rangle_B\right)$$

- After Alice's measurement of the X quadrature

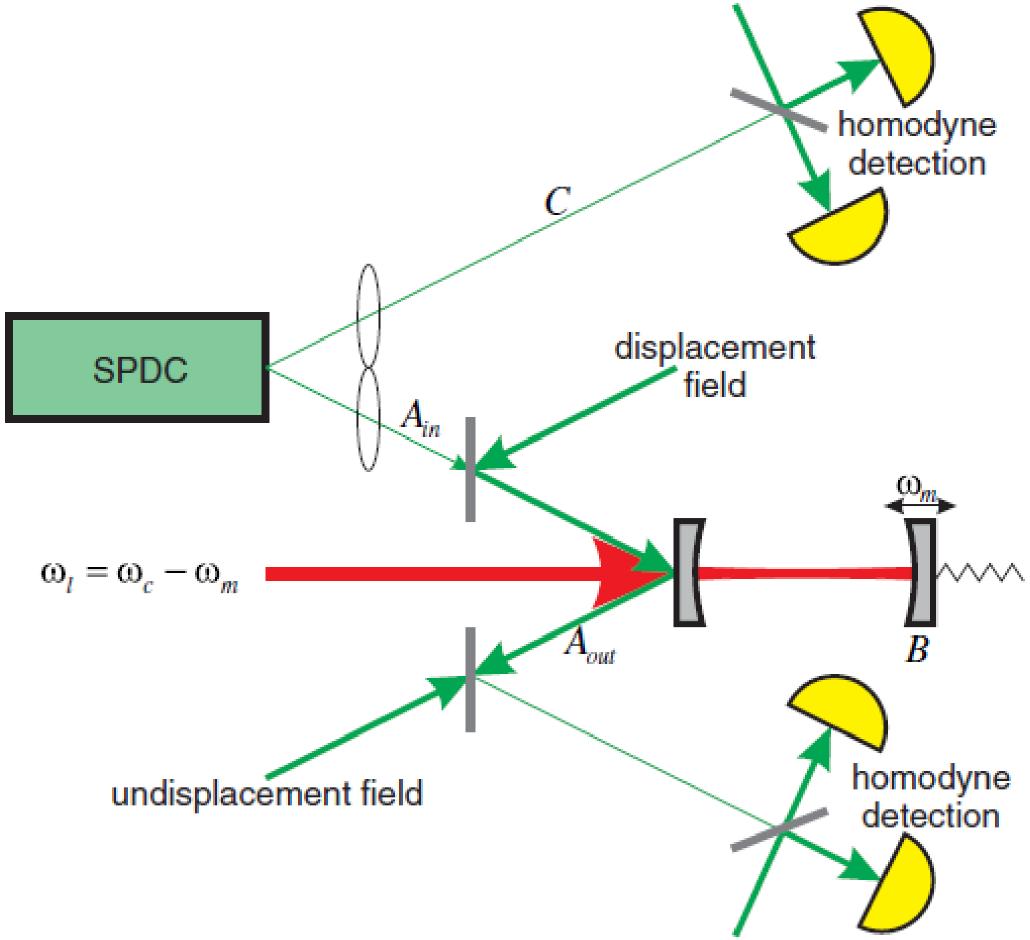
$$|\psi_{\mathrm{B}}\rangle = \frac{1}{\sqrt{2}}\left(\psi_0(X_{\mathrm{A}})\hat{D}(\alpha)\,|1\rangle_{\mathrm{B}} + \psi_1(X_{\mathrm{A}})\hat{D}(\alpha)\,|0\rangle_{\mathrm{B}}\right)$$

- Alice's mode → microscopic state → quadrature measurement.
- Bob's mode → macroscopic phase-space displacement → phase-space un-displacement → quadrature measurement.

(A. I. Lvovsky, R. Ghobadi, A. Chandra, A. S. Prasad and C. Simon, "Observation of micro–macro entanglement of light", Nature Physics 9, 541 (2013)).

An Idea

!!Opto-mechanics!!



(R. Ghobadi, S. Kumar, B. Pepper, D. Bouwmeester, A. I. Lvovsky, and C. Simon, "*Optomechanical Micro-Macro Entanglement*", Phys. Rev. Lett. 112, 080503 (2014)).

Optomechanical storage and retrieval

- The basic opto-mechanical Hamiltonian is :

$$H = \hbar\Delta a^\dagger a + \hbar\omega_m b^\dagger b + \hbar g_0 a^\dagger a(b + b^\dagger)$$

- Effective beam splitter Hamiltonian

$$H_{\text{eff}} = g(a^\dagger b + a b^\dagger)$$

- The resulting equations of motion are :

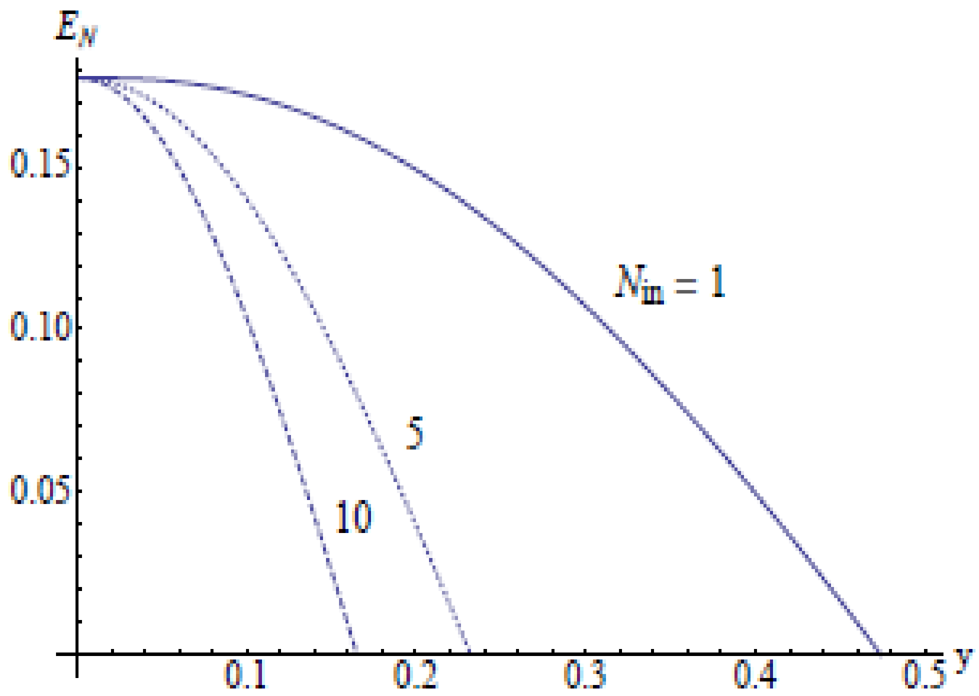
$$\dot{a} = -\kappa a - igb + \sqrt{2\kappa}\, a_{in}$$
$$\dot{b} = -\gamma b - iga + \sqrt{2\gamma}\, b_{in}$$

- The input-output relation for the cavity is

$$a_{out}(t) = -a_{in}(t) + \sqrt{2\kappa}\, a(t).$$

(R. Ghobadi, S. Kumar, B. Pepper, D. Bouwmeester, A. I. Lvovsky, and C. Simon, "*Optomechanical Micro-Macro Entanglement*", Phys. Rev. Lett. 112, 080503 (2014)).

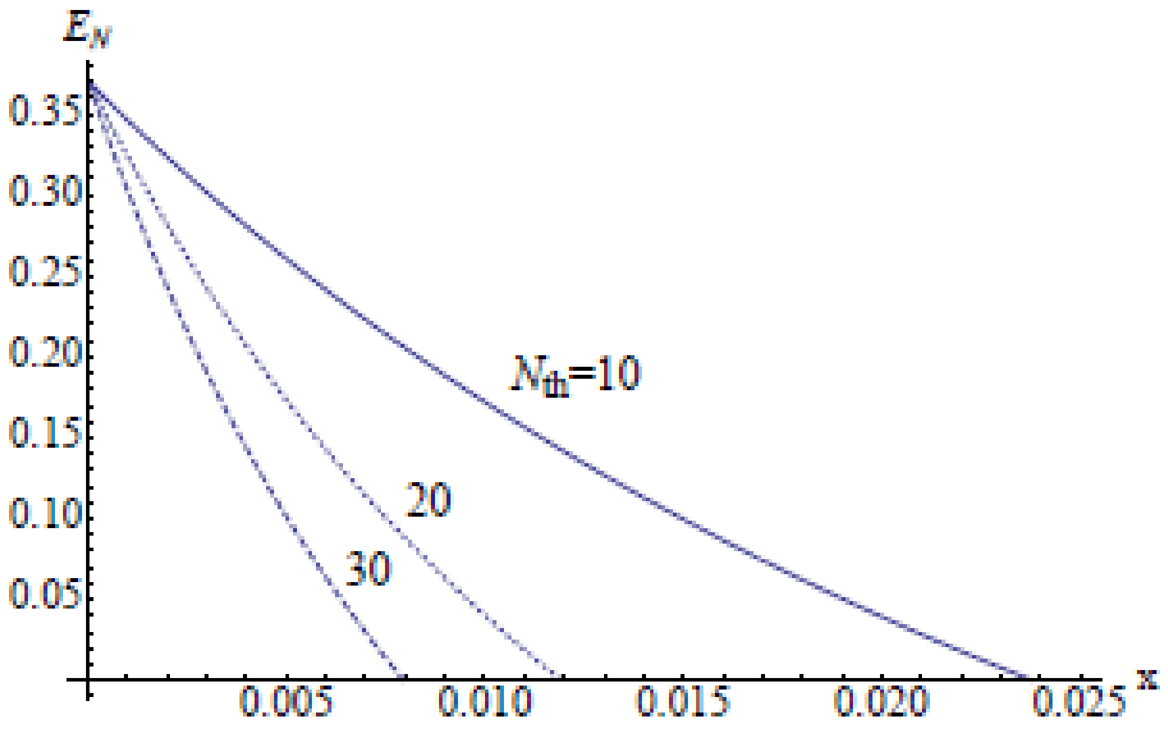
Effects of finite y and mechanical initial state



Entanglement in the final state as a function of the opto-mechanical coupling parameter $y = e^{-G\tau}$ for different values of the initial mechanical phonon number N_{in} .

(R. Ghobadi, S. Kumar, B. Pepper, D. Bouwmeester, A. I. Lvovsky, and C. Simon, "*Optomechanical Micro-Macro Entanglement*", Phys. Rev. Lett. 112, 080503 (2014)).

Entanglement dependence on mechanical noise.



Entanglement in the final state as a function of the mechanical noise parameter $x = \gamma/G$, for different values of the bath mean phonon number *Nth*.

(R. Ghobadi, S. Kumar, B. Pepper, D. Bouwmeester, A. I. Lvovsky, and C. Simon, "*Optomechanical Micro-Macro Entanglement*", Phys. Rev. Lett. 112, 080503 (2014)).

Test of collapse models.

Quantum-gravity induced wavefunction collapse.

- Trampoline resonators

Mass = 500 ng, ω_m = 10 kHz,

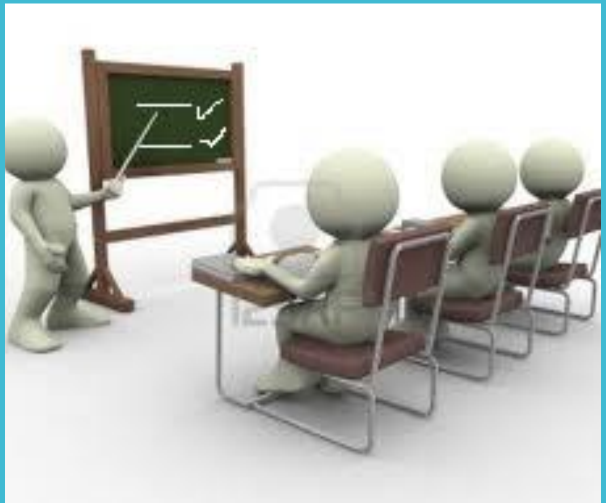
Mechanical quality factor = 10^6

Temperature= 1 mK

Environmentally induced decoherence time scale = 7.6 ms

Quantum gravity induced collapse model = 95 μs – 240 μs

(R. Ghobadi, S. Kumar, B. Pepper, D. Bouwmeester, A. I. Lvovsky, and C. Simon, "*Optomechanical Micro-Macro Entanglement*", Phys. Rev. Lett. 112, 080503 (2014)).



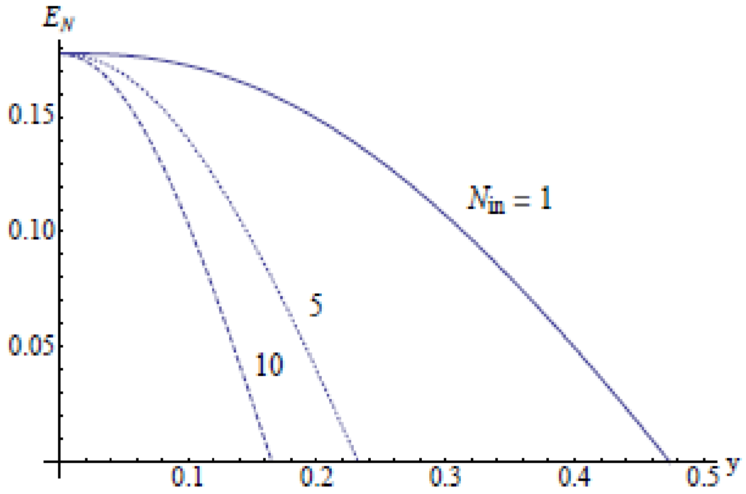
Summary

- Proposal to create and observe an opto-mechanical micro-macro entangled state.
- Studied the most important experimental imperfections (phase noise, mechanical decoherence and photon loss), and found the parameter regime where the demonstration of entanglement is possible.
- Found out that the realization is quite possible using state-of-the-art opto-mechanical systems and entangled light sources.
- Can test unconventional collapse models, e.g. gravitationally induced collapse.

Thank You

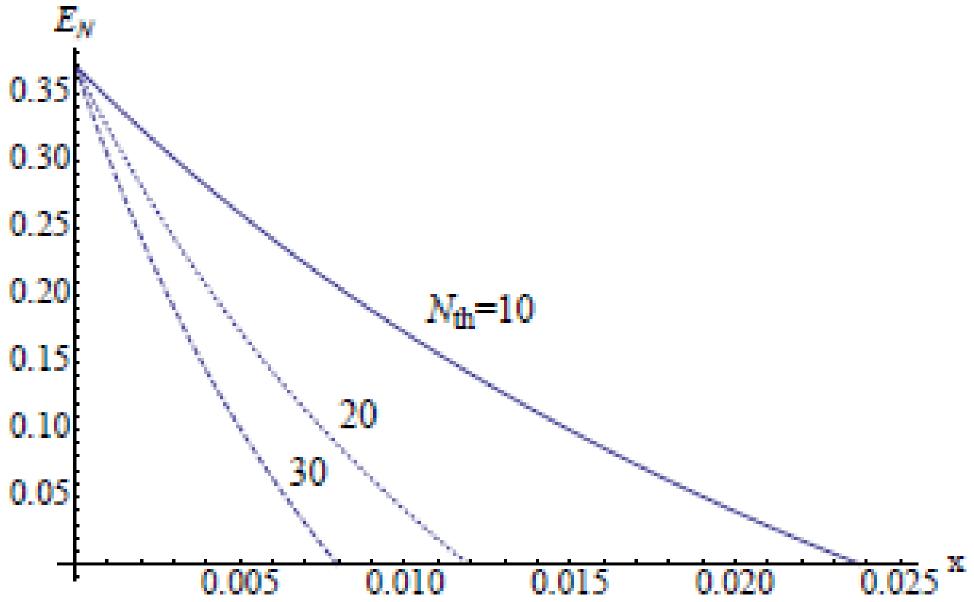
Effects of finite y and mechanical initial state

- :



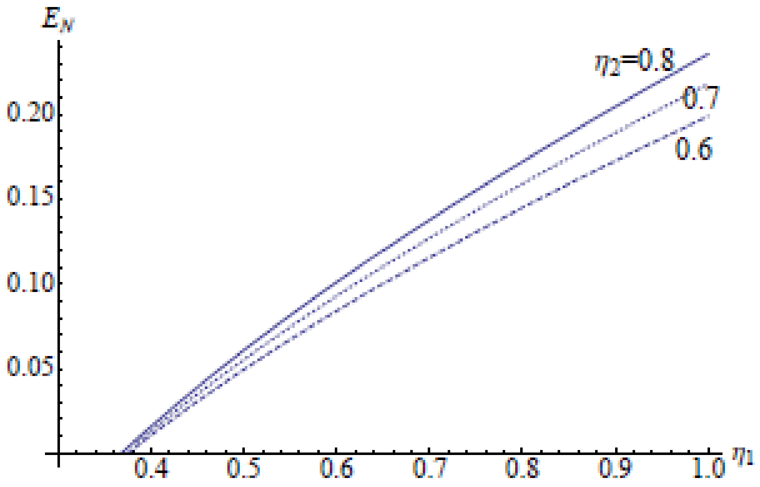
Entanglement in the final state as a function of the opto-mechanical coupling parameter $y = e^{-G\tau}$ for different values of the initial mechanical phonon number N_{in} . In all cases y has to be below a certain threshold value for entanglement to be observable, where the value of the threshold depends on *Nin*. The figure also includes the effect of other imperfections, the relevant parameter values are $x = \gamma/G = 0.01$ and $N_{th} = 10$ (mechanical noise), $\eta_1 = \eta_2 = \eta_c = 0{:}8$ (losses). The photon number corresponding to the displacement is $N_D = |\alpha|^2 = 5000$, and the squeezing parameter is $r = 0{:}5$

Entanglement dependence on mechanical noise.



Entanglement in the final state as a function of the mechanical noise parameter $x = \gamma/G$, for different values of the bath mean phonon number *Nth*. The values of the other parameters are *ND* = = 5000, *r* = 0.5, *y* = 0.1, and η1 = η2 = η*c* = 0.8 (losses).

Photon loss



Entanglement in the final state as a function of η_1 for different values of η_2. Here 1- η_1 and 1 - η_2 are the photon loss before and after the opto-mechanical system respectively. The values of the other parameters are $ND = |\alpha|^2 = 5000$, $r = 0{:}5$, $y = 0.1$, $Nin = 10$, , $x = 0.01$, $Nth = 10$, and $\eta_c = 0.8$.

Implememtation

- ω_m = 3.7 GHz, κ = 500 MHz, and γ = 35 kHz
- T=2 K
- $g \approx$ 40 MHz, $G = g^2/\kappa \approx$ 3.2 MHz
- $x = \gamma/G \approx 0.01$
- $\tau \approx$ 100 ns
- $y = e^{-G\tau} \approx 0.1.$

R. Ghobadi, S. Kumar, B. Pepper, D. Bouwmeester, A. I. Lvovsky, and C. Simon, "*Optomechanical Micro-Macro Entanglement*", Phys. Rev. Lett. 112, 080503 (2014).