

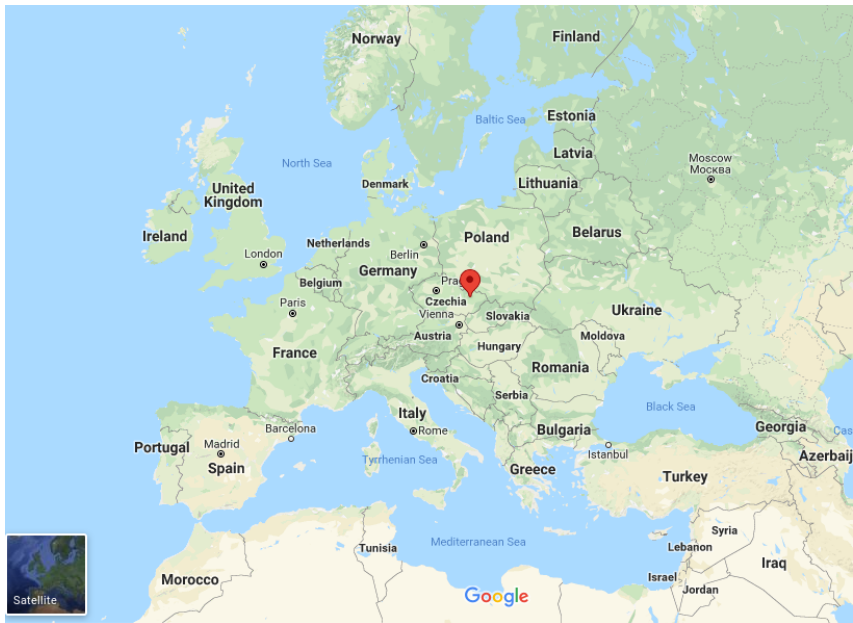
Robust Entanglement With A Thermal Mechanical Oscillator

Andrey A. Rakhubovsky Radim Filip

Department of Optics, Palacký University, Czech Republic

Phys. Rev. A **91**, 062317 (2015).

Quantum Optics Lab
S-Pb, 13.04.2018



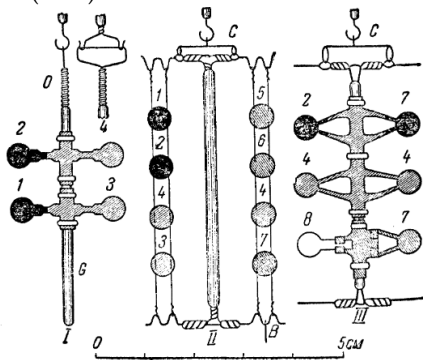
Pressure of Light I

1619 J. Kepler De Cometis Libelli Tres

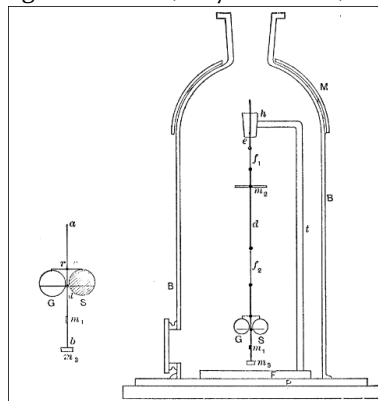
1862 J.C. Maxwell

1901

P.N. Lebedev; "Untersuchungen über die Druckkräfte des Lichtes", Annalen der Physik 6,433 (1901)



E.F. Nichols and G.F. Hull "A preliminary communication on the pressure of heat and light radiation", Phys. Rev. 13, 307 (1901)



Pressure of Light II

1964 V.B. Braginsky, I.I. Minakova, MSU Bulletin **1**, 83 (1964)

1970 V.B. Braginsky, Investigation of dissipative ponderomotive effects of electromagnetic radiation Soviet Physics JETP **31**, 5 (1970)

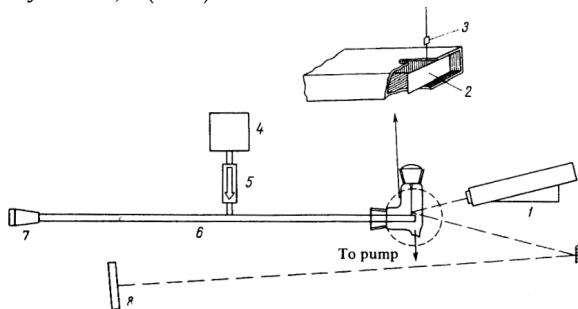
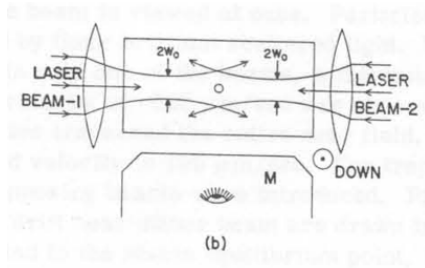


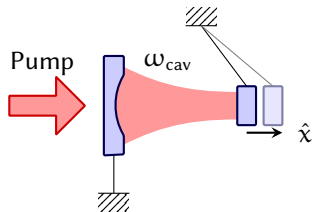
FIG. 1. Schematic diagram of the experimental arrangement: 1—laser, 2—plate-oscillator, 3—mirror, 4—magnetron, 5—ferrite valve, 6—resonator, 7—mobile piston, 8—photographic film.

Pressure of Light III

1970 A. Ashkin, Acceleration and Trapping of Particles by Radiation Pressure. Phys. Rev. Lett. **24**, 156–159 (1970).



Cavity Optomechanics



- ★ Radiation pressure drives mechanical motion
- ★ Mechanical displacement changes optical length of the cavity

Experimental Realizations

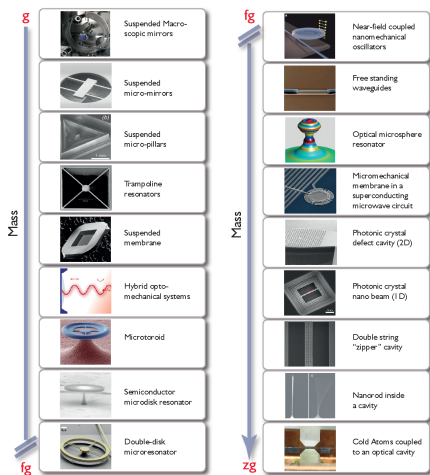


Figure source: ¹

¹Aspelmeyer, Kippenberg and Marquardt, RMP **86**, 1391 (2014)

²Kashkanova *et al.*, Nat. Phys. **13**, 74 (2017)

Experimental Realizations

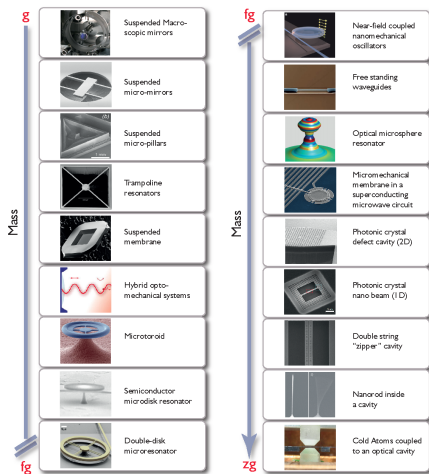


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²Kashkanova *et al.*, Nat. Phys. **13**, 74 (2017)

Experimental Realizations

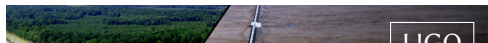
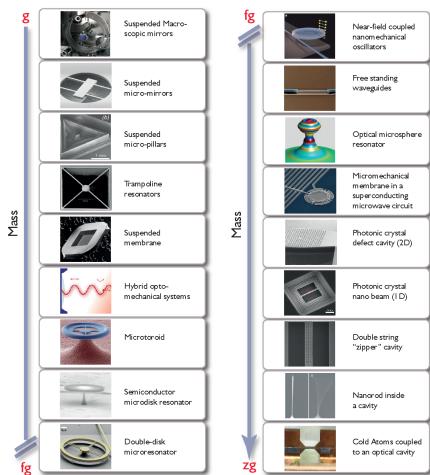


Photo: Bryce
Vickmark
**Rainer
Weiss**
Prize share: 1/2

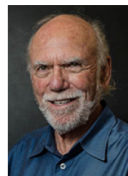


Photo: Caltech
**Barry C.
Barish**
Prize share: 1/4



Photo: Caltech
Alumni
Association
**Kip S.
Thorne**
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Figure source: ¹

¹Aspelmeyer, Kippenberg and Marquardt, RMP **86**, 1391 (2014)

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Experimental Realizations

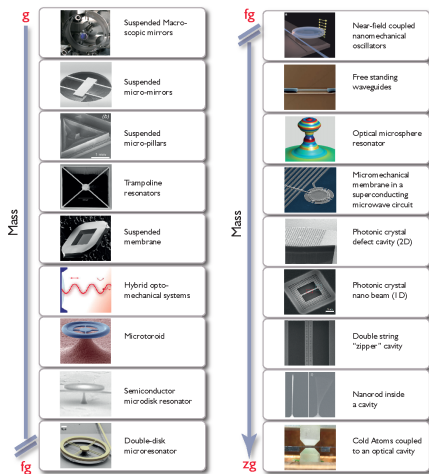


Figure source: ¹

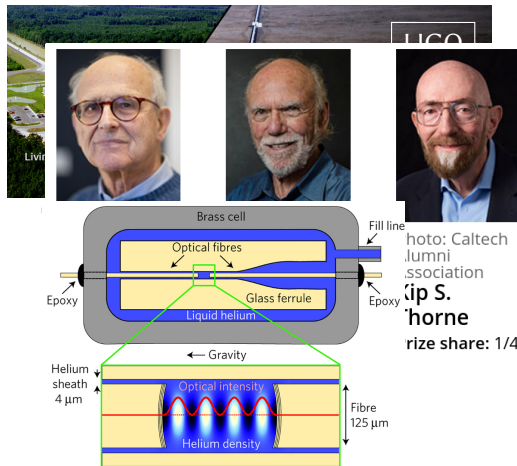


Figure source: ²

¹Aspelmeyer, Kippenberg and Marquardt, RMP **86**, 1391 (2014)

²Kashkanova *et al.*, Nat. Phys. **13**, 74 (2017)

Advantages of Optomechanics for Quantum Information

Uniform Type of Radiation Pressure

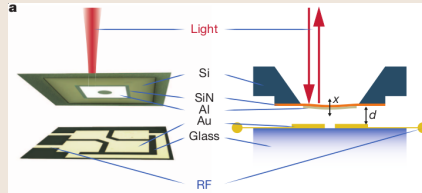


Figure source ³

Nonlinear Mechanical Potential

Strong Coupling (High Cooperativity)

Long Coherence Time

³Bagci *et al.*, Nature **507**, 81 (2014)

Advantages of Optomechanics for Quantum Information

Uniform Type of Radiation Pressure



Can Work at the Quantum Level

- ★ Can capture quantum signals
- ★ Can transduce quantum signals

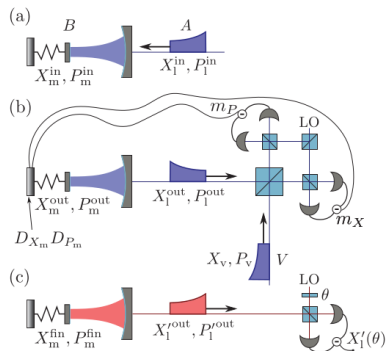
Nonlinear Mechanical Potential

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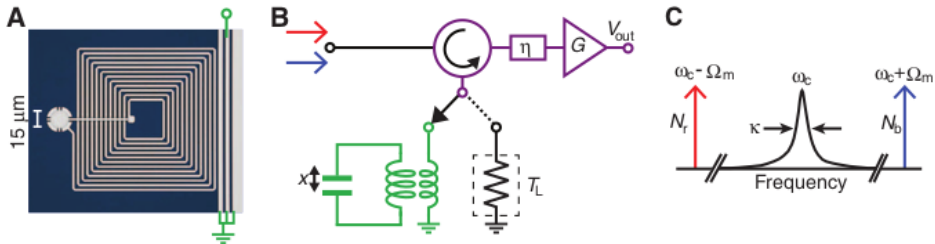
Pulsed Optomechanical Entanglement I

2011 S. G. Hofer, W. Wieczorek, M. Aspelmeyer, K. Hammerer, Quantum entanglement and teleportation in pulsed cavity optomechanics. Phys. Rev. A **84**, 052327 (2011).



Pulsed Optomechanical Entanglement II

2013 T. A. Palomaki, J. D. Teufel, R. W. Simmonds, K. W. Lehnert, Entangling Mechanical Motion with Microwave Fields. *Science* **342**, 710–713 (2013).



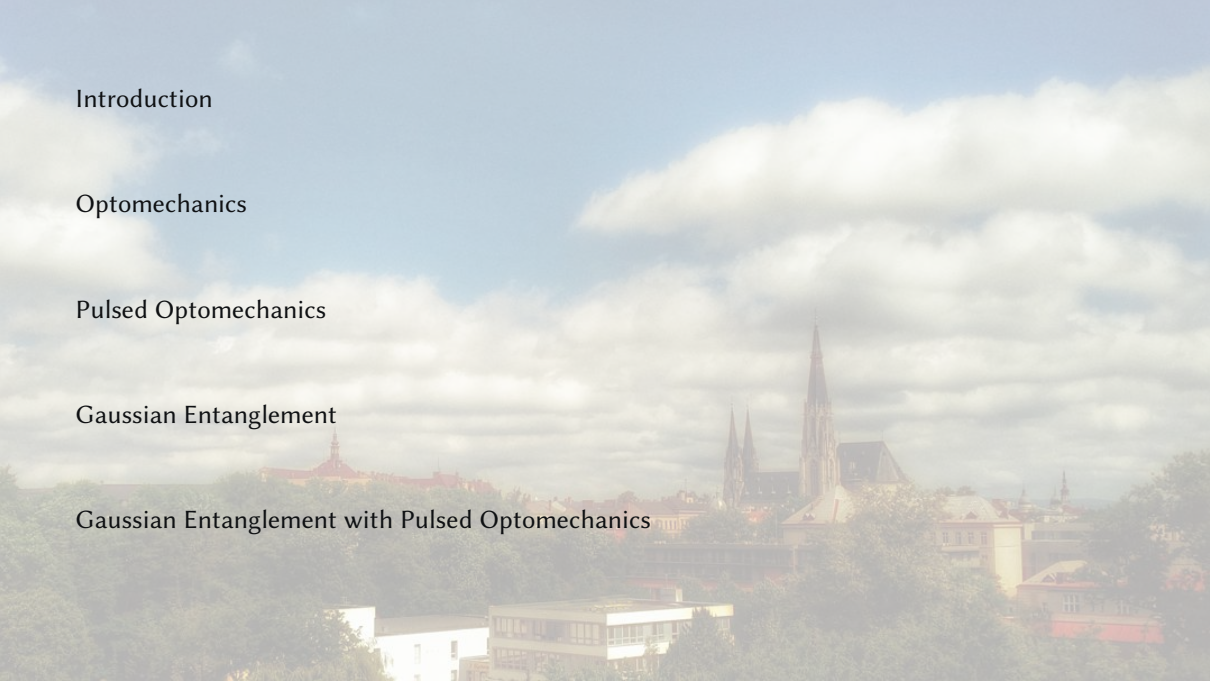
Introduction

Optomechanics

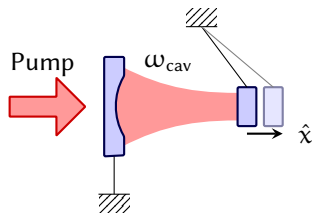
Pulsed Optomechanics

Gaussian Entanglement

Gaussian Entanglement with Pulsed Optomechanics



The Optomechanical systems



Radiation

Standard quantization of the cavity field

$$\hat{\mathbf{E}}(\mathbf{r}, t) = \sum_{\mathbf{p}} \sum_{\mathbf{k}} \mathbf{e}_{\mathbf{p}} u_{\mathbf{k}}(\mathbf{r}) \hat{a}_{\mathbf{k}}(t)$$

Mechanics

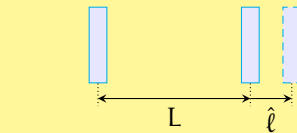
Displacement field

$$\hat{\mathbf{u}}(\mathbf{r}, t) = \sum_{\mathbf{n}} u_{\mathbf{n}}(\mathbf{r}) \hat{x}_{\mathbf{n}}(t)$$

Only one field mode a and one mechanical x_n are considered.

The Hamiltonian

$$H = \hbar\omega_{\text{cav}}(\hat{\ell})a^\dagger a + \hbar\omega_{\text{m}}b^\dagger b$$



a — optical mode

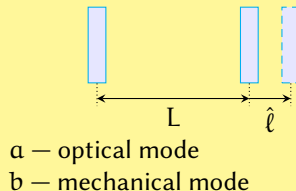
b — mechanical mode

The Hamiltonian

$$\begin{aligned} H &= \hbar\omega_{\text{cav}}(\hat{\ell})a^\dagger a + \hbar\omega_{\text{m}}b^\dagger b \\ &= \hbar\omega_{\text{cav}}a^\dagger a - \hbar\frac{\omega_{\text{cav}}}{L}\hat{\ell}a^\dagger a + \hbar\omega_{\text{m}}b^\dagger b \end{aligned}$$

Modulation of the cavity frequency

$$\omega_{\text{cav}}(\hat{\ell}) = \frac{\pi nc}{L + \hat{\ell}} \approx \frac{\pi nc}{L} \left[1 - \frac{\hat{\ell}}{L} \right] = \omega_{\text{cav}} - \hat{\ell} \frac{\omega_{\text{cav}}}{L}.$$

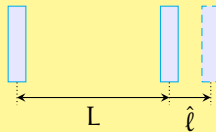


The Hamiltonian

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a – optical mode

b – mechanical mode

$$\hat{\ell} = \sqrt{\frac{\hbar}{2m\omega_{\text{m}}}}(b + b^\dagger)$$

$$\hat{\Phi} = \sqrt{\frac{\hbar m \omega_{\text{m}}}{2}}(b - b^\dagger)/i$$

$$[\hat{\ell}, \hat{\Phi}] = i\hbar$$

The Hamiltonian

$$\begin{aligned} H &= \hbar\omega_{\text{cav}}(\hat{\ell})a^\dagger a + \hbar\omega_m b^\dagger b \\ &= \hbar\omega_{\text{cav}}a^\dagger a - \hbar\frac{\omega_{\text{cav}}}{L}\hat{\ell}a^\dagger a + \hbar\omega_m b^\dagger b \end{aligned}$$

Modulation of the cavity frequency

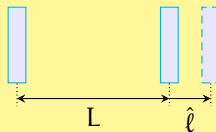
$$\omega_{\text{cav}}(\hat{\ell}) = \frac{\pi n c}{L + \hat{\ell}} \approx \frac{\pi n c}{L} \left[1 - \frac{\hat{\ell}}{L} \right] = \omega_{\text{cav}} - \hat{\ell} \frac{\omega_{\text{cav}}}{L}.$$

In dimensionless units

$$H_{\text{int}} = -\hbar\omega_{\text{cav}} \frac{\chi_{\text{zpf}}}{L} (b + b^\dagger) a^\dagger a = -\hbar g_0 (b + b^\dagger) a^\dagger a.$$

With the single-photon coupling strength

$$g_0 = \omega_{\text{cav}} \frac{\chi_{\text{zpf}}}{L} = \omega_{\text{cav}} \sqrt{\frac{\hbar}{2m\omega_m L^2}}$$



a – optical mode

b – mechanical mode

$$\hat{\ell} = \sqrt{\frac{\hbar}{2m\omega_m}} (b + b^\dagger) = \chi_{\text{zpf}} x$$

$$\hat{\Phi} = \sqrt{\frac{\hbar m \omega_m}{2}} (b - b^\dagger)/i$$

$$[\hat{\ell}, \hat{\Phi}] = i\hbar$$

$$x = b + b^\dagger; \quad p = (b - b^\dagger)/i,$$

$$[x, p] = 2i.$$

$$\text{Var}[x]_{|0\rangle} \equiv \langle 0 | (x - \bar{x})^2 | 0 \rangle = 1.$$

Modulation of the cavity frequency

$$\omega_{\text{cav}}(\hat{\ell}) = \frac{\pi n c}{L + \hat{\ell}} \approx \frac{\pi n c}{L} \left[1 - \frac{\hat{\ell}}{L} \right] = \omega_{\text{cav}} - \hat{\ell} \frac{\omega_{\text{cav}}}{L}.$$

In dimensionless units

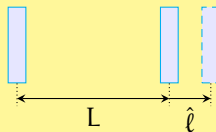
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With the single-photon coupling strength

$$g_0 = \omega_{\text{cav}} \frac{\chi_{\text{zpf}}}{L} = \omega_{\text{cav}} \sqrt{\frac{\hbar}{2m\omega_m L^2}}$$

With $m = 10 \text{ ng}$, $\omega_m = 1 \text{ MHz}$, $L = 10 \text{ mm}$,

$$\chi_{\text{zpf}} \sim 0.1 \text{ fm}, g_0 \sim 10 \text{ Hz}.$$



a – optical mode

b – mechanical mode

$$\hat{\ell} = \sqrt{\frac{\hbar}{2m\omega_m}} (b + b^\dagger) = \chi_{\text{zpf}} x$$

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In dimensionless units

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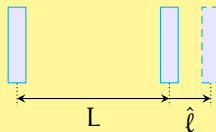
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With $m = 10 \text{ ng}$, $\omega_m = 1 \text{ MHz}$, $L = 10 \text{ mm}$,

$$\chi_{\text{zpf}} \sim 0.1 \text{ fm}, g_0 \sim 10 \text{ Hz}.$$

Too weak \Rightarrow enhance by strong pump and linearize.



a – optical mode

b – mechanical mode

$$\hat{\ell} = \sqrt{\frac{\hbar}{2m\omega_m}} (b + b^\dagger) = \chi_{\text{zpf}} x$$

$$\hat{\Phi} = \sqrt{\frac{\hbar m \omega_m}{2}} (b - b^\dagger)/i$$

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$$\text{Var}[x]_{|0\rangle} \equiv \langle 0 | (x - \bar{x})^2 | 0 \rangle = 1.$$

Assume strong classical driving of the cavity @ ω_p

$\epsilon \propto$ power of the pump

$$H = \hbar\omega_{\text{cav}}a^\dagger a + \hbar\omega_m b^\dagger b - \hbar g_0 a^\dagger a (b^\dagger + b) - \hbar\epsilon \left(a^\dagger e^{-i\omega_p t} + \text{h.c.} \right) \quad \Delta \equiv \omega_{\text{cav}} - \omega_p - \text{detuning}$$

At frame defined by $H = \hbar\omega_p a^\dagger a$:

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

Assume strong classical driving of the cavity @ ω_p

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At frame defined by $H = \hbar\omega_p a^\dagger a$:

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

After substitutions

$$a \rightarrow \alpha + \delta a$$

$$b \rightarrow \beta + \delta b$$

$$H = \hbar \underbrace{\left[\Delta - \frac{2\alpha^2 g_0^2}{\omega_m} \right]}_{\Delta} \delta a^\dagger \delta a + \hbar\omega_m \delta b^\dagger \delta b - \hbar g_0 \left[\alpha(\delta a^\dagger + \delta a) + \cancel{\delta a^\dagger \delta a} \right] (\delta b^\dagger + \delta b).$$

$$\alpha = \frac{\epsilon}{\Delta + 2\beta g_0}, \beta = \text{Homework.}$$

Assume strong classical driving of the cavity @ ω_p

$\epsilon \propto$ power of the pump

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$$\alpha = \frac{\epsilon}{\Delta + 2\beta g_0}, \beta = \text{Homework.}$$

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

$$g \equiv g_0 \alpha = g_0 \sqrt{n_p}$$

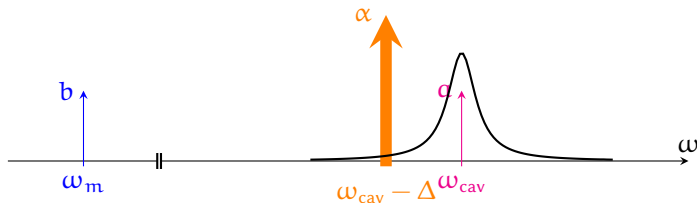
Linearized Optomechanics

The Hamiltonian

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

The main participants

- a quantum optical mode at ω_{cav}
- α strong classical pump at $\omega_{\text{cav}} - \Delta$
- b quantized mechanical motion at ω_m



$$H = \underbrace{\hbar\Delta a^\dagger a + \hbar\omega_m b^\dagger b}_{H_{\text{RF}}} - \hbar g(a^\dagger + a)(b^\dagger + b)$$

$$a \rightarrow ae^{-i\Delta t}; \quad b \rightarrow be^{-i\omega_m t};$$

$$H = \underbrace{\hbar\Delta a^\dagger a + \hbar\omega_m b^\dagger b}_{H_{\text{RF}}} - \hbar g(a^\dagger + a)(b^\dagger + b)$$

$$a \rightarrow ae^{-i\Delta t}; \quad b \rightarrow be^{-i\omega_m t};$$

$$H = -\hbar g(abe^{-i(\Delta+\omega_m)} + \text{h.c.}) \\ - \hbar g(ab^\dagger e^{-i(\Delta-\omega_m)} + \text{h.c.})$$

$$\Delta = \omega_{\text{cav}} - \omega_p$$

$$H = \underbrace{\hbar\Delta a^\dagger a + \hbar\omega_m b^\dagger b}_{H_{\text{RF}}} - \hbar g(a^\dagger + a)(b^\dagger + b)$$

$$a \rightarrow ae^{-i\Delta t}; \quad b \rightarrow be^{-i\omega_m t};$$

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$$\Delta = \omega_{\text{cav}} - \omega_p$$

In the Rotating Wave Approximation (RWA) (assuming g small)
Lower sideband pump $\Delta = +\omega_m$

$$H = -\hbar g(ab^\dagger + abe^{-2i\omega_m t}) + \text{h.c.} \\ \approx -\hbar g[ab^\dagger + a^\dagger b]$$

$$H = \underbrace{\hbar\Delta a^\dagger a + \hbar\omega_m b^\dagger b}_{H_{\text{RF}}} - \hbar g(a^\dagger + a)(b^\dagger + b)$$

$$a \rightarrow ae^{-i\Delta t}; \quad b \rightarrow be^{-i\omega_m t};$$

$$H = -\hbar g(abe^{-i(\Delta+\omega_m)} + \text{h.c.}) \\ - \hbar g(ab^\dagger e^{-i(\Delta-\omega_m)} + \text{h.c.})$$

$$\Delta = \omega_{\text{cav}} - \omega_p$$

In the Rotating Wave Approximation (RWA) (assuming g small)

Lower sideband pump $\Delta = +\omega_m$

Upper sideband pump $\Delta = -\omega_m$

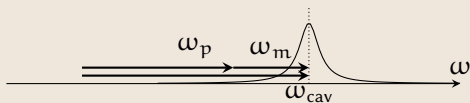
$$H = -\hbar g(ab^\dagger + abe^{-2i\omega_m t}) + \text{h.c.} \\ \approx -\hbar g[ab^\dagger + a^\dagger b]$$

$$H = -\hbar g(ab^\dagger e^{2i\omega_m t} + ab) + \text{h.c.} \\ \approx -\hbar g[ab + a^\dagger b^\dagger].$$

Resonantly detuned optomechanics

Lower Mechanical Sideband

$$\omega_p = \omega_{\text{cav}} - \omega_m$$



$$H \propto ab^\dagger + a^\dagger b$$

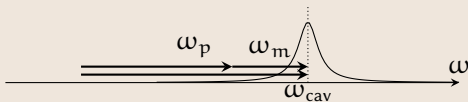
- ★ Parametric Converter / Beam-splitter
- ★ State swap / Cooling

Resolved sideband $\kappa \ll \omega_m$

Resonantly detuned optomechanics

Lower Mechanical Sideband

$$\omega_p = \omega_{\text{cav}} - \omega_m$$



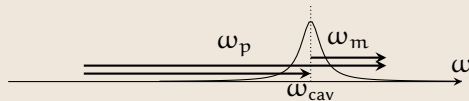
$$H \propto ab^\dagger + a^\dagger b$$

- ★ Parametric Converter / Beam-splitter
- ★ State swap / Cooling

Resolved sideband $\kappa \ll \omega_m$

Upper Mechanical Sideband

$$\omega_p = \omega_{\text{cav}} + \omega_m$$



$$H = ab + a^\dagger b^\dagger$$

- ★ Parametric Amp / Two-mode squeezing
- ★ Entanglement

Digression: Optical Spring

Radiation Pressure Force

$$\begin{aligned}F_{\text{RP}}(t) &\propto P(x) = -Kx \\&= -Kx(t - \tau_*) \\&\approx -K \times (x - \tau_* \dot{x}) = -Kx + \Gamma \dot{x}\end{aligned}$$

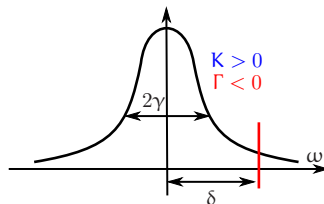
Digression: Optical Spring

Radiation Pressure Force

$$\begin{aligned}
 F_{\text{RP}}(t) &\propto P(x) = -Kx \\
 &= -Kx(t - \tau_*) \\
 &\approx -K \times (x - \tau_* \dot{x}) = -Kx + \Gamma \dot{x}
 \end{aligned}$$

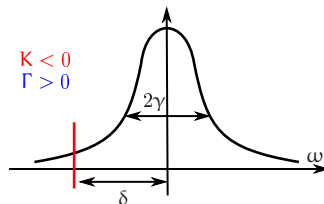
Электромагнитная жесткость впервые наблюдалась В. Б. Брагинским³

Настройка на правый склон



Положительная жесткость и
отрицательное затухание

Настройка на левый склон



Отрицательная жесткость и
положительное затухание

► Назад

³V.B. Braginsky, I.I. Minakova Bull. MSU III 1, 83 (1964)

А. Рахубовский (физфак МГУ)

Introduction

Optomechanics

Pulsed Optomechanics

Gaussian Entanglement

Gaussian Entanglement with Pulsed Optomechanics



Environment

Optical Environment



κ_{ext} detection channel, κ_L losses

Interacts with the modes of travelling light,
(almost) each in vacuum. Collective operator a_i

$$[a_i(t), a_i^\dagger(t')] = \delta(t - t');$$

$$\frac{1}{2} \langle a_i(t) a_i^\dagger(t') + a_i^\dagger(t') a_i(t) \rangle = 1.$$

Typically the cavity is overcoupled with

$$\kappa_{\text{ext}} \gg \kappa_L$$

Environment

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Typically the cavity is overcoupled with
 $\kappa_{\text{ext}} \gg \kappa_L$

Mechanical Environment

Q-factor:

$$Q_{\text{tot}}^{-1} = Q_{\text{clamp}}^{-1} + Q_{\text{mat}}^{-1} + Q_{\text{air}}^{-1} + Q_{\text{scat}}^{-1} + \dots$$

At rate $\gamma = \omega_m/Q$ coupled to a thermal bath
 with bosonic operator b^{th} :

$$\begin{aligned} [b^{\text{th}}(t), b^{\text{th}\dagger}(t')] &= \delta(t - t'), \\ \frac{1}{2} \langle \{b^{\text{th}}(t), b^{\text{th}\dagger}(t')\} \rangle &= (2n_{\text{th}} + 1)\delta(t - t'). \end{aligned}$$

$$n_{\text{th}} = \frac{1}{\exp[\hbar\omega_m/k_B T] - 1} \approx k_B T / \hbar\omega_m$$

Equations of motion

Assume red detuning $\omega_p = \omega_{\text{cav}} - \omega_m$, therefore $H = -\hbar g(ab^\dagger + a^\dagger b)$.

$$\dot{a} = igb - \kappa a + \sqrt{2\kappa}a^{\text{in}},$$

$$\dot{b} = iga - \frac{\gamma}{2}b + \sqrt{\gamma}b^{\text{th}}$$

Input-output relation for optics $a^{\text{out}} = -a^{\text{in}} + \sqrt{2\kappa}a$

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Define $\mathbf{a} = (a, b)$, \mathbb{A} , $\mathbf{f} = (\sqrt{2\kappa}a^{\text{in}}, \sqrt{\gamma}b^{\text{th}})$, then

$$\dot{\mathbf{a}} = \mathbb{A}.\mathbf{a} + \mathbf{f}$$

Formal solution (with $\mathbb{M}(s) = \exp[-\mathbb{A}s]$)

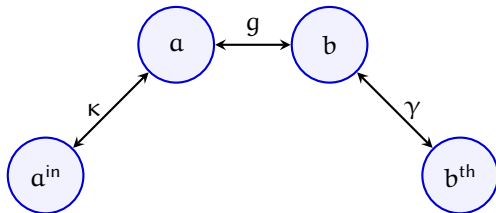
$$\mathbf{a}(t) = \mathbb{M}(t)\mathbf{a}(0) + \int_0^t ds \mathbb{M}(t-s).\mathbf{f}(s).$$

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Input-output relation for optics $a^{\text{out}} = -a^{\text{in}} + \sqrt{2\kappa}a$



Parameters:

- ★ Resolved sideband $\kappa \ll \omega_m$
- ★ Weak coupling $g \sim 10^{-3 \div -1} \kappa$
- ★ Slow mechanical decay $\gamma \sim 10^{-7 \div -4} \kappa$
- ★ Not too hot bath $\gamma n_{\text{th}} \leq \{g, \kappa\}$

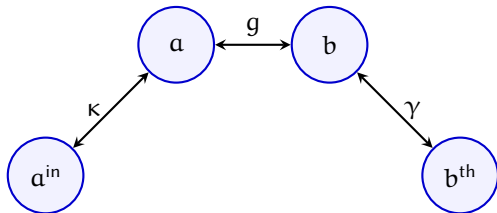
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That is,

- ★ mechanical decay can be approximately ignored

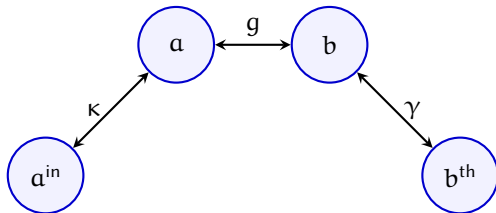
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Input-output relation for optics $a^{\text{out}} = -a^{\text{in}} + \sqrt{2\kappa}a$



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That is,

- ★ mechanical decay can be approximately ignored
- ★ cavity mode can be adiabatically eliminated

$$\begin{aligned}0 &= igb - \kappa a + \sqrt{2\kappa}a^{\text{in}}, \\ \dot{b} &= ig a.\end{aligned}$$

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$$\begin{aligned}a &= i\frac{g}{\kappa}b + \sqrt{\frac{2}{\kappa}}a^{\text{in}}, \\ \dot{b} &= -Gb + i\sqrt{2G}a^{\text{in}}, \quad G \equiv g^2/\kappa\end{aligned}$$

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$$A^{\text{out}} = \sqrt{\frac{2G}{1 - e^{-2G\tau}}} \int_0^\tau d\xi a^{\text{out}}(\xi)e^{-G\xi}; \quad [A^{\text{out}}, A^{\text{out}\dagger}] = 1.$$

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$$\begin{aligned} \int_0^\tau dt a^{\text{out}}(t)e^{-Gt} &= \int_0^\tau dt a^{\text{in}}(t)e^{-Gt} + i\sqrt{2G}b(0) \int_0^\tau dt e^{-2Gt} \\ &\quad - 2G \int_0^\tau dt e^{-2Gt} \int_0^t d\xi a^{\text{in}}(\xi)e^{G\xi} \end{aligned}$$

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$$= i\sqrt{1-e^{-2G\tau}}b(0) + e^{-G\tau}A^{\text{in}}.$$

$$\begin{aligned}B^{\text{out}} &= \sqrt{T}B^{\text{in}} + i\sqrt{1-T}A^{\text{in}}, \\A^{\text{out}} &= \sqrt{T}A^{\text{in}} + i\sqrt{1-T}B^{\text{in}}.\end{aligned}$$

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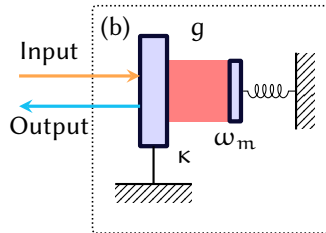
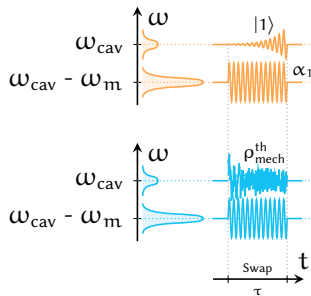
$$B^{\text{in}} = b(0); \quad B^{\text{out}} = b(\tau),$$

$$A^{\text{out}} = \sqrt{\frac{2G}{1 - e^{-2G\tau}}} \int_0^\tau dt \, a^{\text{out}}(t) e^{-Gt}$$

$$A^{\text{in}} = \sqrt{\frac{2G}{e^{2G\tau} - 1}} \int_0^\tau d\xi \, a^{\text{in}}(\xi) e^{G\xi},$$

$$T \equiv e^{-2G\tau}, \quad G = g^2/\kappa.$$

Pulsed State Swap



Pulsed Entanglement

Blue tuning (to the upper sideband, $\omega_p = \omega_{\text{cav}} + \omega_m$).

$$H = -\hbar g(ab + a^\dagger b^\dagger)$$

In a similar fashion, assuming no thermal decoherence and adiabatic elimination of cavity mode,

$$A^{\text{out}} = \sqrt{K}A^{\text{in}} + i\sqrt{K-1}B^{\text{in}\dagger},$$

$$B^{\text{out}} = \sqrt{K}B^{\text{in}} + i\sqrt{K-1}A^{\text{in}\dagger},$$

Two-Mode Squeezed State (ideally, vacuum: TMSV).

$$A^{\text{in}} = \sqrt{\frac{2G}{1 - e^{-2G\tau}}} \int_0^\tau dt a^{\text{in}}(t) e^{-Gt},$$

$$A^{\text{out}} = \sqrt{\frac{2G}{e^{2G\tau} - 1}} \int_0^\tau dt a^{\text{out}}(t) e^{Gt}.$$

The Protocol

Classical pump @ ω_p , quantum cavity mode @ ω_{cav} , mechanical mode @ ω_m .

In the rotating frame we deal with slow amplitudes

Pump power $\mapsto g(t) \mapsto$ Temporal mode profile

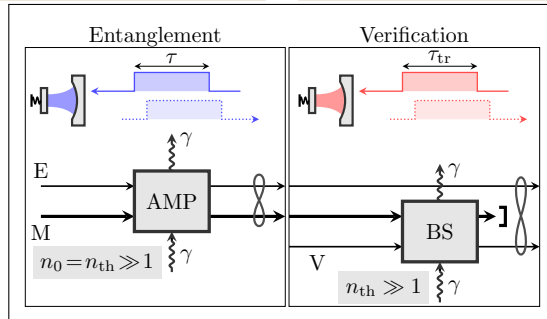
For nice exponential envelopes assume constant pump

Blue detuning $\omega_p = \omega_{\text{cav}} + \omega_m$

Two-Mode squeezing interaction

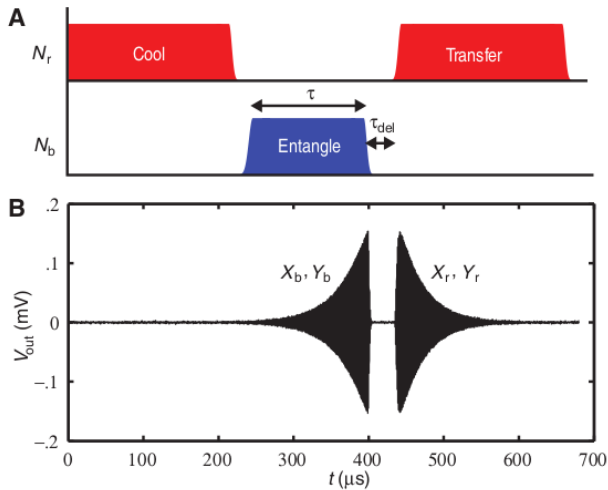
Red detuning $\omega_p = \omega_{\text{cav}} - \omega_m$

State swap interaction



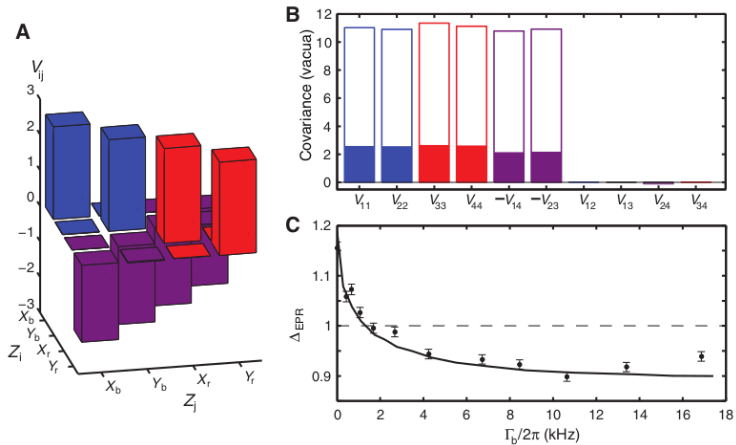
Evaluation

[Palomaki,2013] following [Hofer, 2011] evaluate the Duan's variance:



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By expressing Eqs. (7) in terms of quadratures $X_m^i = (B_i + B_i^\dagger)/\sqrt{2}$ and $X_1^i = (A_i + A_i^\dagger)/\sqrt{2}$, where $i \in \{\text{in}, \text{out}\}$, and their corresponding conjugate variables, we can calculate the so-called EPR variance Δ_{EPR} of the state after the interaction. For light initially in vacuum $(\Delta X_1^{\text{in}})^2 = (\Delta P_1^{\text{in}})^2 = \frac{1}{2}$ and the mirror in a thermal state $(\Delta X_m^{\text{in}})^2 = (\Delta P_m^{\text{in}})^2 = n_0 + \frac{1}{2}$, the state is entangled iff [52]

$$\begin{aligned} \Delta_{\text{EPR}} &= [\Delta(X_m^{\text{out}} + P_1^{\text{out}})]^2 + [\Delta(P_m^{\text{out}} + X_1^{\text{out}})]^2 \\ &= 2(n_0 + 1)(e^r - \sqrt{e^{2r} - 1})^2 < 2, \end{aligned} \quad (8)$$

Evaluation

[Palomaki,2013] following [Hofer, 2011] evaluate the Duan's variance:

$$\hat{u} = |a|\hat{x}_1 + \frac{1}{a}\hat{x}_2,$$

$$\hat{v} = |a|\hat{p}_1 - \frac{1}{a}\hat{p}_2,$$

Theorem 1.—Sufficient criterion for inseparability: For any separable quantum state ρ , the total variance of a pair of EPR-like operators defined by Eqs. (2a) and (2b) with the commutators $[\hat{x}_j, \hat{p}_{j'}] = i\delta_{jj'}$ ($j, j' = 1, 2$) satisfies the inequality

$$\langle(\Delta\hat{u})^2\rangle_\rho + \langle(\Delta\hat{v})^2\rangle_\rho \geq a^2 + \frac{1}{a^2}. \quad (3)$$

Evaluation

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A proper criterion has to be applied!

Either the properly generalized Duan variance or logarithmic negativity

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Introduction

Optomechanics

Pulsed Optomechanics

Gaussian Entanglement

Gaussian Entanglement with Pulsed Optomechanics



Continuous Variables Systems

Each mode is described by annihilation operator a_k :

$$[a_i, a_j^\dagger] = \delta_{ij}; \quad [a_i, a_j] = [a_i^\dagger, a_j^\dagger] = 0.$$

Or quadratures

$$x_k = a_k + a_k^\dagger; \quad p_k = (a_k - a_k^\dagger)/i,$$

which form the vector

$$\mathbf{R} = \{x_1, p_1, x_2, p_2, \dots, x_N, p_N\}.$$

$$[R_i, R_j] = 2i\Omega_{ij}; \quad \Omega_{ij} = \bigoplus_{k=1}^N \omega; \quad \omega = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}.$$

Gaussian states: $\langle \mathbf{R} \rangle$ and covariance matrix

$$\mathbb{V}_{ij} = \frac{1}{2} \langle \{ (R_i - \langle R_i \rangle), (R_j - \langle R_j \rangle) \} \rangle \mapsto \frac{1}{2} \langle R_i R_j + R_j R_i \rangle, \text{ if } \mathbf{R} = 0.$$

Bipartite Gaussian System

$$\mathbf{R} = (\mathbf{x}_1, \mathbf{p}_1, \mathbf{x}_2, \mathbf{p}_2), \quad [\mathbf{x}_1, \mathbf{p}_1] = 2i; \quad [\mathbf{x}_2, \mathbf{p}_2] = 2i;$$

Assuming $\langle \mathbf{R} \rangle = 0$,

$$\mathbb{V} = \left(\begin{array}{cc|cc} \langle \mathbf{x}_1^2 \rangle & \langle \mathbf{x}_1 \circ \mathbf{p}_1 \rangle & \langle \mathbf{x}_1 \circ \mathbf{x}_2 \rangle & \langle \mathbf{x}_1 \circ \mathbf{p}_2 \rangle \\ \langle \mathbf{p}_1 \circ \mathbf{x}_1 \rangle & \langle \mathbf{p}_1^2 \rangle & \langle \mathbf{p}_1 \circ \mathbf{x}_2 \rangle & \langle \mathbf{p}_1 \circ \mathbf{p}_2 \rangle \\ \hline \langle \mathbf{x}_2 \circ \mathbf{x}_1 \rangle & \langle \mathbf{x}_2 \circ \mathbf{p}_1 \rangle & \langle \mathbf{x}_2^2 \rangle & \langle \mathbf{x}_2 \circ \mathbf{p}_2 \rangle \\ \langle \mathbf{p}_2 \circ \mathbf{x}_1 \rangle & \langle \mathbf{p}_2 \circ \mathbf{p}_1 \rangle & \langle \mathbf{p}_2 \circ \mathbf{x}_2 \rangle & \langle \mathbf{p}_2^2 \rangle \end{array} \right), \quad \text{where } \mathbf{a} \circ \mathbf{b} \equiv \frac{1}{2}(\mathbf{a}\mathbf{b} + \mathbf{b}\mathbf{a}).$$

Bipartite Gaussian System

$$\mathbf{R} = (x_1, p_1, x_2, p_2), \quad [x_1, p_1] = 2i; \quad [x_2, p_2] = 2i;$$

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Symplectic Transformations

Transformation $\mathbf{R} \mapsto \mathbf{S}\mathbf{R}$ is symplectic, if

$$\mathbf{S}^T \Omega \mathbf{S} = \Omega$$

Important symplectic transformation diagonalizes the CM

$$\mathbb{V} = \mathbf{S}^T \mathbb{N} \mathbf{S}; \quad \mathbb{N} = \text{diag}(\nu_1, \nu_1, \nu_2, \nu_2, \dots).$$

ν_k : symplectic eigenvalues

A physical state has all $\nu_k \geq \sigma_{\text{vac}}$ (shot-noise variance).

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ν_k : symplectic eigenvalues

A physical state has all $\nu_k \geq \sigma_{\text{vac}}$ (shot-noise variance).

$$\sigma_{\text{vac}} \equiv \langle 0 | \chi^2 | 0 \rangle = \langle (\mathbf{a} + \mathbf{a}^\dagger)^2 \rangle_{|0\rangle} = 1.$$

If e.g. define $\chi = (\mathbf{a} + \mathbf{a}^\dagger)/\sqrt{2}$, then $\sigma_{\text{vac}} = 1/2$.

Entanglement and Partial Transposition

A bipartite state ρ is separable if (otherwise, entangled)

$$\hat{\rho} = \sum_i p_i \hat{\rho}_i^A \otimes \hat{\rho}_i^B$$

Entanglement is a resource etc.

Entanglement and Partial Transposition

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Partial Transposition

If $\hat{\rho}$ is physical, so is $\hat{\rho}^T$

Idea: check transposition of a subsystem (Peres-Horodecki)

$$\hat{\rho}^{T_B} = \sum_i p_i \hat{\rho}_i^A \otimes (\hat{\rho}_i^B)^T$$

If $\hat{\rho}^{T_B}$ is physical, the state is separable

Partial Transposition and CM

In a CV system partial transposition is equivalent to reversing time:

$$x \rightarrow x; \quad p \rightarrow -p$$

Criterion of physicality: all symplectic eigenvalues $\nu_k \geq 1$.

$$\mathbb{V} = \begin{pmatrix} V_1 & V_c \\ V_c^T & V_2 \end{pmatrix}$$

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$$\nu_{\pm} = \frac{1}{\sqrt{2}} \left[\Sigma(\mathbb{V}) - \sqrt{\Sigma(\mathbb{V})^2 - 4 \det \mathbb{V}} \right]^{1/2}$$

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$$\Sigma(\mathbb{V}) \equiv \det V_1 + \det V_2 - 2 \det V_c.$$

$$E_N = \max[-\log \nu_- / \sigma_{\text{vac}}, 0].$$

The background of the slide is a photograph of a cityscape, likely Prague, featuring a prominent church with a tall, dark spire. The city is nestled among green trees, and the sky is filled with large, white, fluffy clouds. The overall tone is soft and slightly hazy.

Introduction

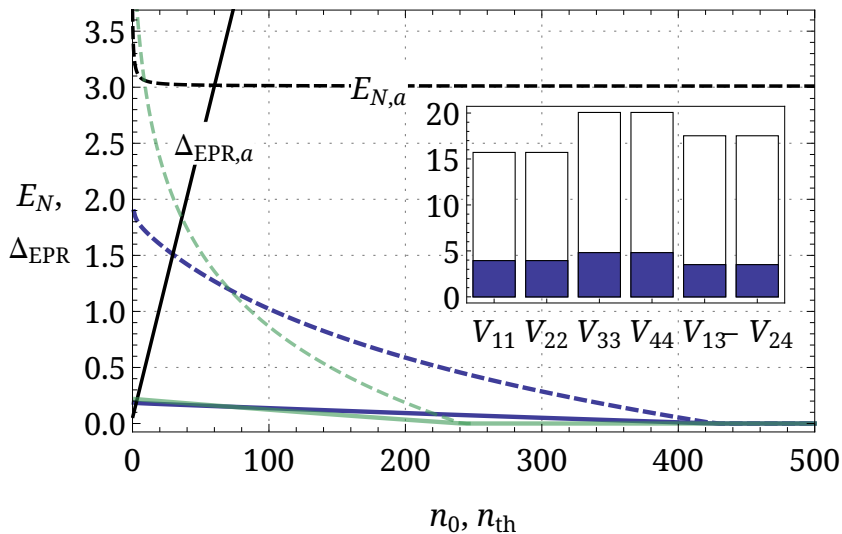
Optomechanics

Pulsed Optomechanics

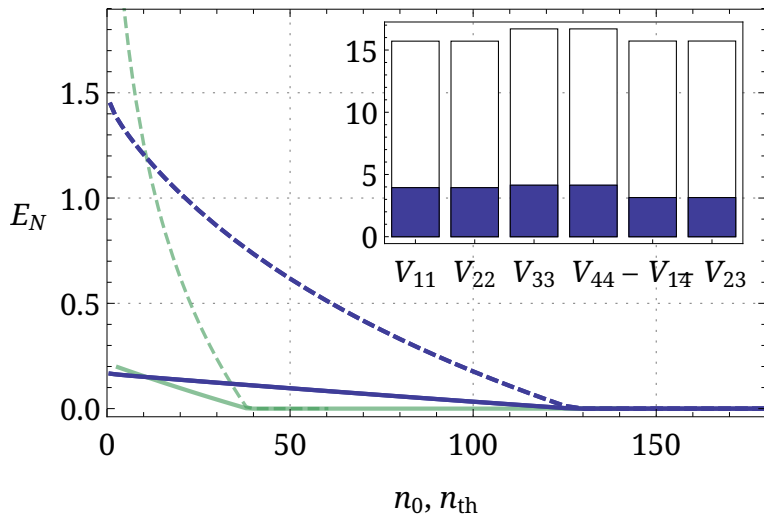
Gaussian Entanglement

Gaussian Entanglement with Pulsed Optomechanics

Opto- (Electro-) Mechanical Entanglement



Pulses Entanglement



Conclusion

Robust Entanglement Is Robust

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Optomechanics: Important theory

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