Robust Entanglement With A Thermal Mechanical Oscillator

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Quantum Optics Lab
S-Pb, 13.04.2018


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Hungary
France
Romania
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Serbia
Black Sea
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Georgia
Barcelona
Rome
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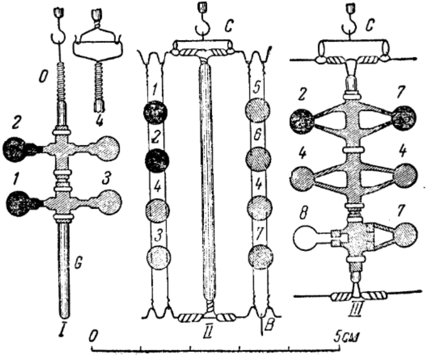
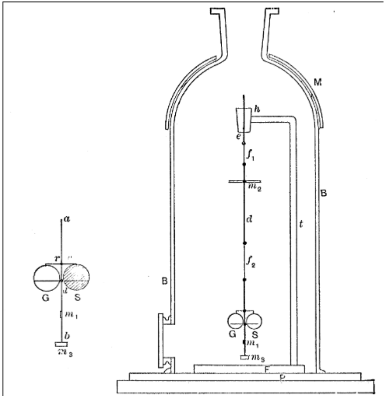
Pressure of Light I

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)

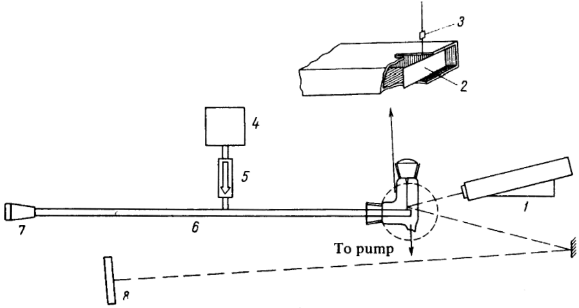
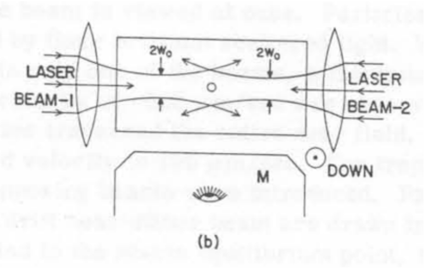


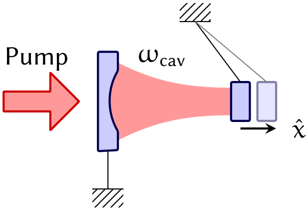
FIG. 1. Schematic diagram of the experimental arrangement: 1–laser, 2–plate-oscillator, 3–mirror, 4–magnetron, 5–ferrite valve, 6–resonator, 7–mobile piston, 8–photographic film.

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

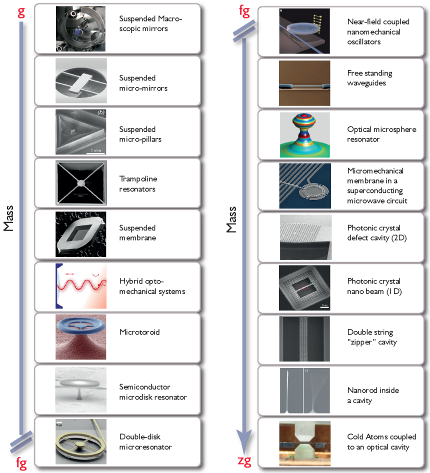
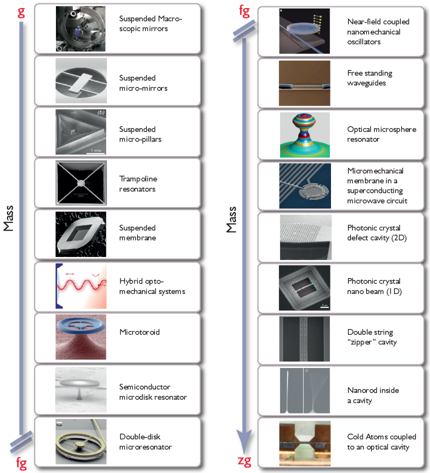


Figure source: [1]

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

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

Experimental Realizations



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Experimental Realizations

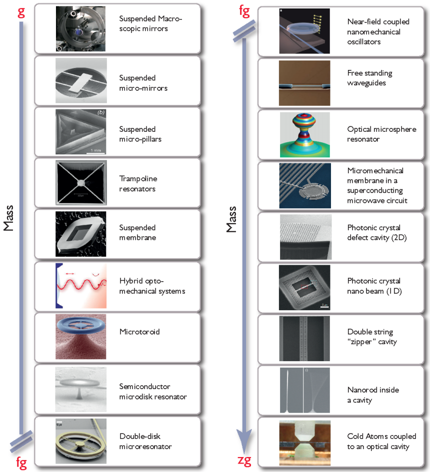

Photo: Bryce Vickmark
Rainer Weiss
Prize share: 1/2

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

Photo: Caltech Alumni Association
Kip S. Thorne
Prize share: 1/4

Figure source: [1]

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

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Experimental Realizations

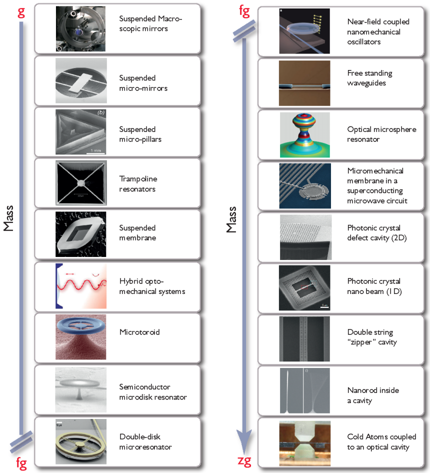
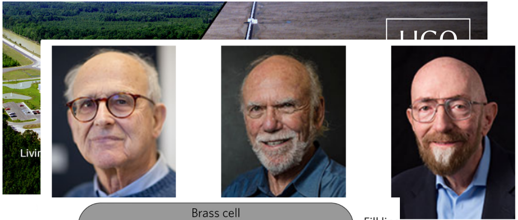


Figure source: [1]



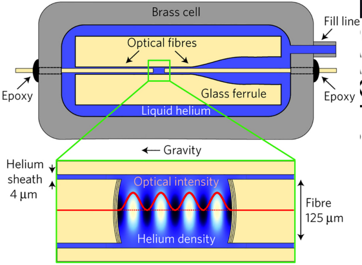


Figure source: [2]

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

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

Advantages of Optomechanics for Quantum Information

Uniform Type of Radiation Pressure

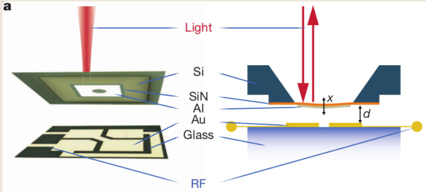


Figure source [3]

Nonlinear Mechanical Potential

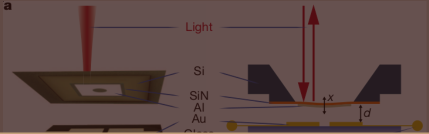
Strong Coupling (High Cooperativity)

Long Coherence Time

[3] Bagci *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

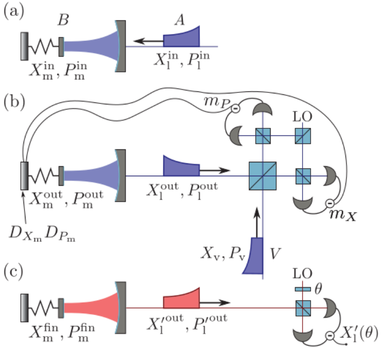
Strong Coupling (High Cooperativity)

Long Coherence Time

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

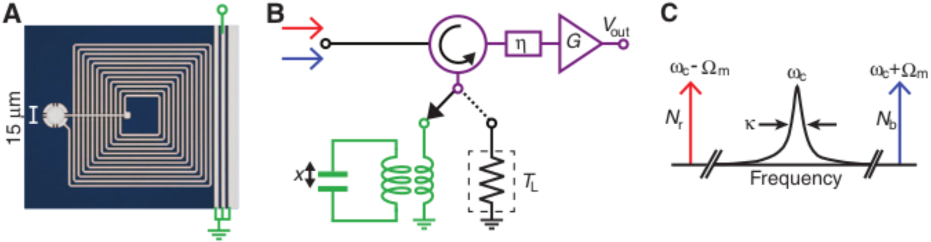
Pulsed Optomechanical Entanglement I

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



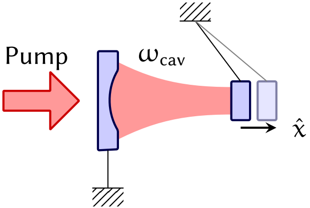
Pulsed Optomechanical Entanglement II

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

$$\hat{E}(\mathbf{r}, t) = \sum_p \sum_k \mathbf{e}_p u_k(\mathbf{r}) \hat{a}_k(t)$$

Mechanics

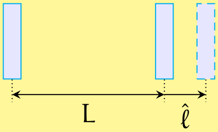
Displacement field

$$\hat{\mathbf{u}}(\mathbf{r}, t) = \sum_n u_n(\mathbf{r}) \hat{x}_n(t)$$

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

The Hamiltonian

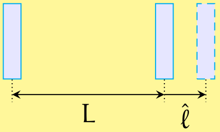
$$H = \hbar\omega_{cav}(\hat{\ell})a^\dagger a + \hbar\omega_m b^\dagger b$$



a — optical mode
b — mechanical mode

The Hamiltonian

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



a — optical mode
b — mechanical mode

Modulation of the cavity frequency

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

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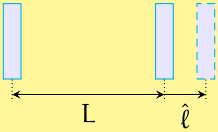

a — optical mode
b — mechanical mode

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

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

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

The Hamiltonian

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

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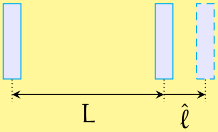
In dimensionless units

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

With the single-photon coupling strength

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



a — optical mode
b — mechanical mode

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

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

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

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

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

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

Modulation of the cavity frequency

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

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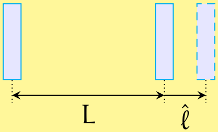
With the single-photon coupling strength

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

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

$x_{\mathrm{zpf}} \sim 0.1$ fm, $g_0 \sim 10$ Hz.



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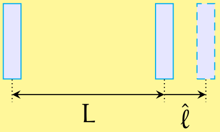
With $m = 10$ ng, $\omega_m = 1$ MHz, $L = 10$ mm,

$x_{\mathrm{zpf}} \sim 0.1$ fm, $g_0 \sim 10$ Hz.

Too weak $\Rightarrow$ enhance by strong pump and linearize.



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Assume strong classical driving of the cavity @ω_p

$\epsilon \propto$ power of the pump

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

$\Delta \equiv \omega_{cav} - \omega_p$ – detuning

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

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

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After substitutions

$a \to \alpha + \delta a$
$b \to \beta + \delta b$

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

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

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

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

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

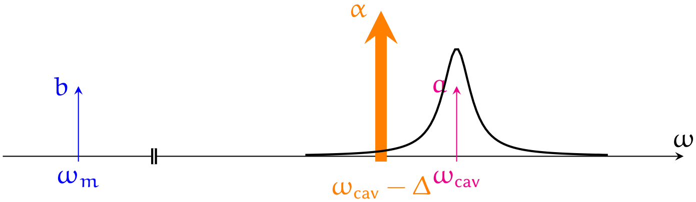
Linearized Optomechanics

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 $\omega_{cav} - \Delta$
- b quantized mechanical motion at ω_m



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

$$a \to a e^{-i\Delta t}; \quad b \to b e^{-i\omega_m t};$$

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

$$a \to a e^{-i\Delta t}; \quad b \to b e^{-i\omega_m t};$$

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

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

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

$$a \to a e^{-i\Delta t}; \quad b \to b e^{-i\omega_m t};$$

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

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

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

Lower sideband pump $\Delta = +\omega_m$

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

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

$$a \to a e^{-i\Delta t}; \quad b \to b e^{-i\omega_m t};$$

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

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

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

Lower sideband pump $\Delta = +\omega_m$

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

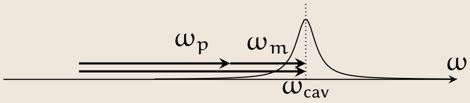
Upper sideband pump $\Delta = -\omega_m$

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

Resonantly detuned optomechanics

Lower Mechanical Sideband

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



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

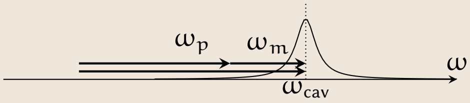
- Parametric Converter / Beam-splitter
- State swap / Cooling

Resolved sideband $\kappa \ll \omega_m$

Resonantly detuned optomechanics

Lower Mechanical Sideband

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

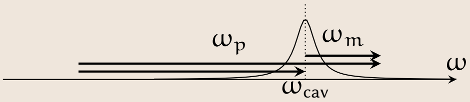


$$H \propto ab^\dagger + a^\dagger b$$

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

Upper Mechanical Sideband

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



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

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

Resolved sideband $\kappa \ll \omega_m$

Digression: Optical Spring

Radiation Pressure Force

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

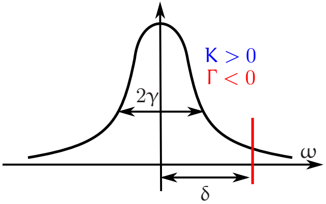
Digression: Optical Spring

Radiation Pressure Force

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

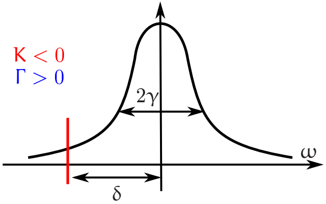
Электромагнитная жесткость впервые наблюдалась В. Б. Брагинским [3]

Настройка на правый склон



Положительная жесткость и отрицательное затухание

Настройка на левый склон



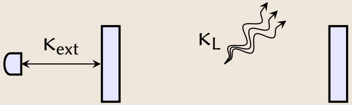
Отрицательная жесткость и положительное затухание

▸ Назад

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

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

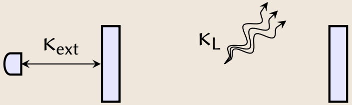
$$\left[a_i(t), a_i^\dagger(t')\right] = \delta(t-t');$$

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

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

Environment

Optical Environment



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Mechanical Environment

Q-factor:

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

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

$$\left[b^{th}(t), b^{th\dagger}(t')\right] = \delta(t-t'),$$

$$\frac{1}{2}\left\langle\left\{b^{th}(t), b^{th\dagger}(t')\right\}\right\rangle = (2n_{th}+1)\delta(t-t').$$

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

Equations of motion

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

$$\dot{a} = igb - \kappa a + \sqrt{2\kappa}a^{in},$$
$$\dot{b} = iga - \frac{\gamma}{2}b + \sqrt{\gamma}b^{th}$$

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

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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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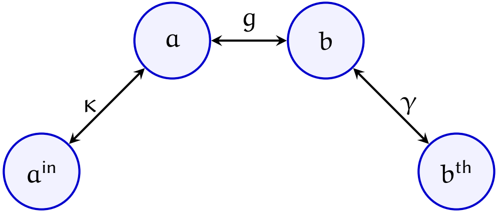

Parameters:

- 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 $\gamma n_{th} \leqslant \{g, \kappa\}$

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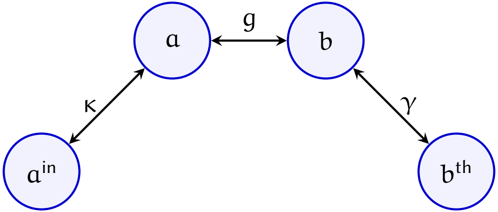

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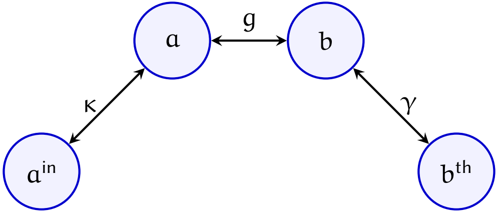

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That is,

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

$$
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$$
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a &= i\frac{g}{\kappa}b + \sqrt{\frac{2}{\kappa}}a^{\mathrm{in}}, \\
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$$a^{\text{out}}(t) = a^{\text{in}}(t) + i\sqrt{2G}b(t) = a^{\text{in}}(t) + i\sqrt{2G}\underline{b(0)e^{-Gt}} - 2Ge^{-Gt}\int_0^t d\xi\, a^{\text{in}}(\xi)e^{G\xi}.$$

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$$\int_0^\tau dt\, a^{\mathrm{out}}(t)e^{-Gt} = \int_0^\tau dt\, a^{\mathrm{in}}(t)e^{-Gt} + i\sqrt{2G}b(0)\int_0^\tau dt\, e^{-2Gt} - 2G\int_0^\tau dt\, e^{-2Gt}\int_0^t d\xi\, a^{\mathrm{in}}(\xi)e^{G\xi}$$

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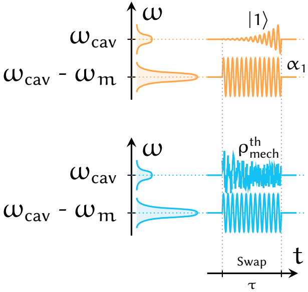
$$A^{out} = \sqrt{T} A^{in} + i\sqrt{1-T} B^{in}.$$

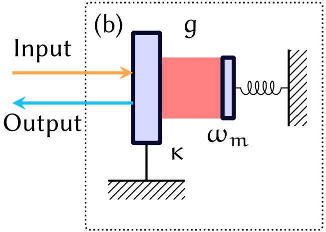
$$B^{in} = b(0); \quad B^{out} = b(\tau),$$

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

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

Pulsed State Swap





Pulsed Entanglement

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

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

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

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

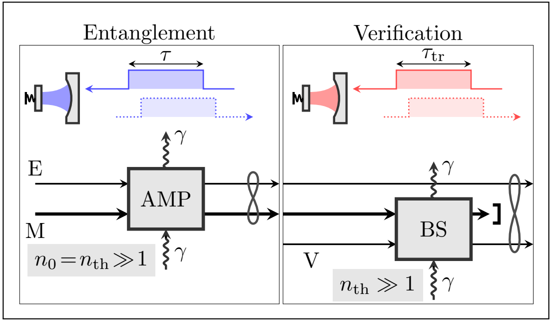
Two-Mode Squeezed State (ideally, vacuum: TMSV).

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

The Protocol

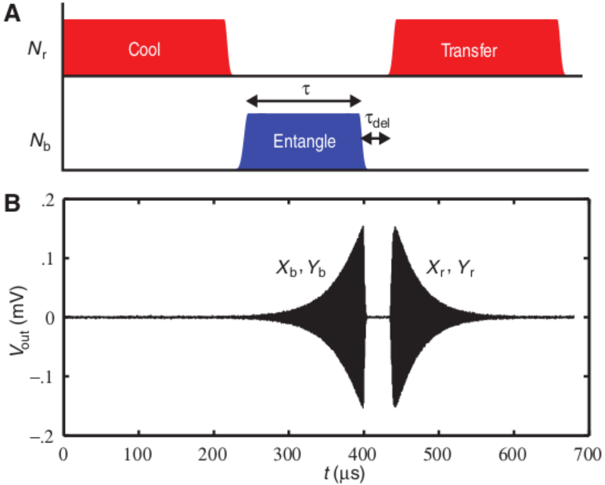
Classical pump @ω_p, quantum cavity mode @ω_{cav}, mechanical mode @ω_m.
In the rotating frame we deal with slow amplitudes
Pump power $\mapsto g(t) \mapsto$ Temporal mode profile
For nice exponential envelopes assume constant pump

Blue detuning $\omega_p = \omega_{cav} + \omega_m$	Red detuning $\omega_p = \omega_{cav} - \omega_m$
Two-Mode squeezing interaction	State swap interaction



Evaluation

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



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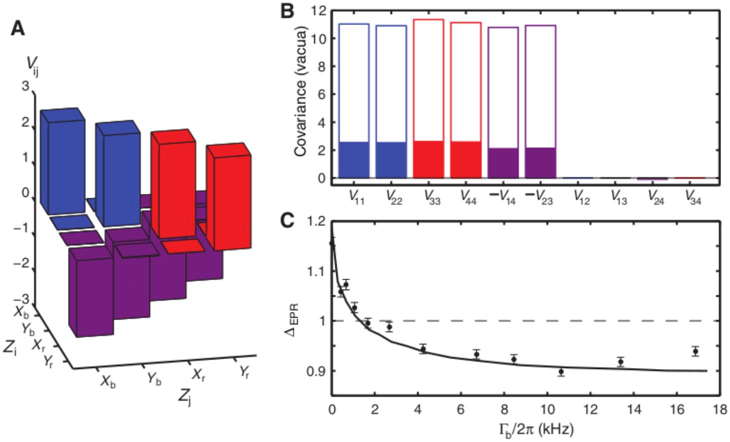

Evaluation

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

By expressing Eqs. (7) in terms of quadratures $X_{\mathrm{m}}^{i} = (B_i + B_i^{\dagger})/\sqrt{2}$ and $X_{\mathrm{l}}^{i} = (A_i + A_i^{\dagger})/\sqrt{2}$, where $i \in \{\mathrm{in}, \mathrm{out}\}$, 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 $(\Delta X_{\mathrm{l}}^{\mathrm{in}})^2 = (\Delta P_{\mathrm{l}}^{\mathrm{in}})^2 = \frac{1}{2}$ and the mirror in a thermal state $(\Delta X_{\mathrm{m}}^{\mathrm{in}})^2 = (\Delta P_{\mathrm{m}}^{\mathrm{in}})^2 = n_0 + \frac{1}{2}$, the state is entangled iff [52]

$$\begin{aligned}\Delta_{\mathrm{EPR}} &= \left[\Delta\left(X_{\mathrm{m}}^{\mathrm{out}} + P_{\mathrm{l}}^{\mathrm{out}}\right)\right]^2 + \left[\Delta\left(P_{\mathrm{m}}^{\mathrm{out}} + X_{\mathrm{l}}^{\mathrm{out}}\right)\right]^2 \\ &= 2(n_0 + 1)\left(e^r - \sqrt{e^{2r} - 1}\right)^2 < 2, \end{aligned} \tag{8}$$

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

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

Evaluation

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

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

A proper criterion has to be applied!

Either the properly generalized Duan variance or logarighmic negativity

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Continuous Variables Systems

Each mode is described by annihilation operator a_k:

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

Or quadratures

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

which form the vector

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

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

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

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

Bipartite Gaussian System

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

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

$$\mathbb{V} = \left(\begin{array}{cc|cc} \langle x_1^2 \rangle & \langle x_1 \circ p_1 \rangle & \langle x_1 \circ x_2 \rangle & \langle x_1 \circ p_2 \rangle \\ \langle p_1 \circ x_1 \rangle & \langle p_1^2 \rangle & \langle p_1 \circ x_2 \rangle & \langle p_1 \circ p_2 \rangle \\ \hline \langle x_2 \circ x_1 \rangle & \langle x_2 \circ p_1 \rangle & \langle x_2^2 \rangle & \langle x_2 \circ p_2 \rangle \\ \langle p_2 \circ x_1 \rangle & \langle p_2 \circ p_1 \rangle & \langle p_2 \circ x_2 \rangle & \langle p_2^2 \rangle \end{array} \right), \qquad \text{where } a \circ b \equiv \frac{1}{2}(ab + ba).$$

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Symplectic Transformations

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

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

Important symplectic transformation diagonalizes the CM

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

ν_k: symplectic eigenvalues
A physical state has all $\nu_k \geqslant \sigma_{\mathrm{vac}}$ (shot-noise variance).

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$$\sigma_{\mathrm{vac}} \equiv \left\langle 0 \middle| x^2 \middle| 0 \right\rangle = \left\langle (a + a^\dagger)^2 \right\rangle_{|0\rangle} = 1.$$

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

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.

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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:

$$x \to x; \quad p \to -p$$

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

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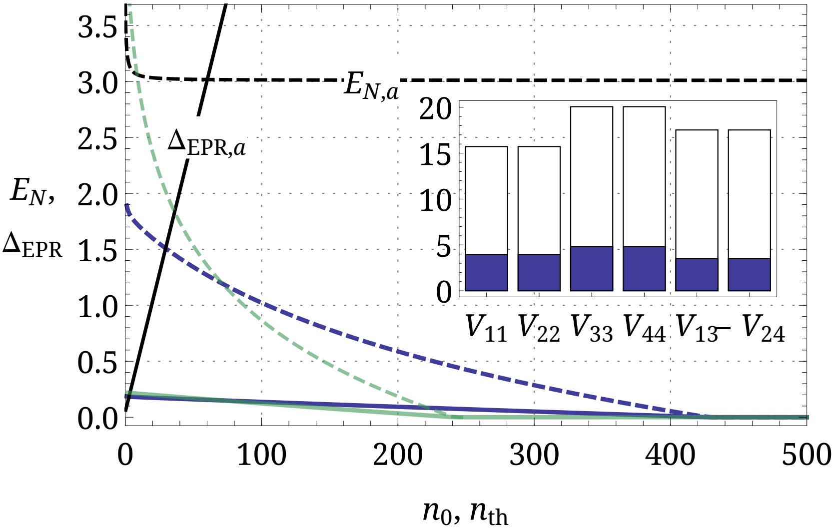
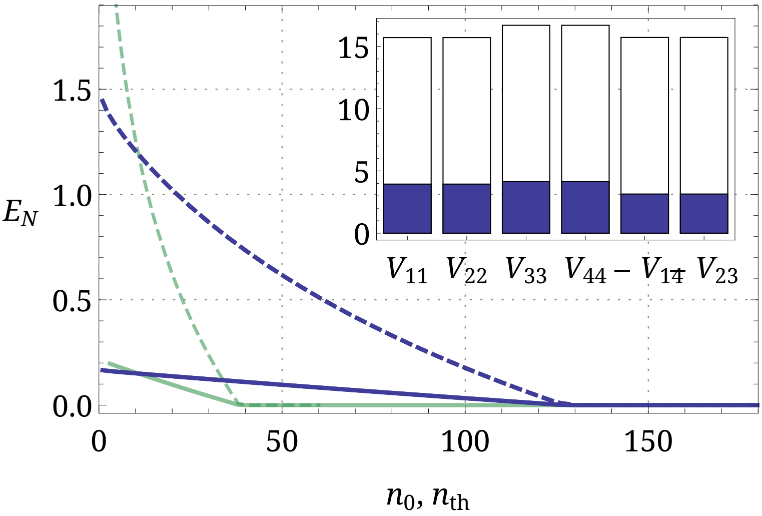
$$E_N = \max[-\log \nu_- / \sigma_{vac}], 0].$$

Opto- (Electro-) Mechanical Entanglement



Pulses Entanglement



Conclusion

Robust Entanglement Is Robust

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