Robust Entanglement With A Thermal Mechanical Oscillator

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

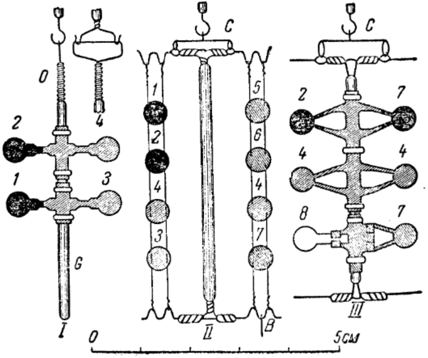
Quantum Optics Lab
S-Pb, 13.04.2018

These slides: `https://goo.gl/EvXbzE`

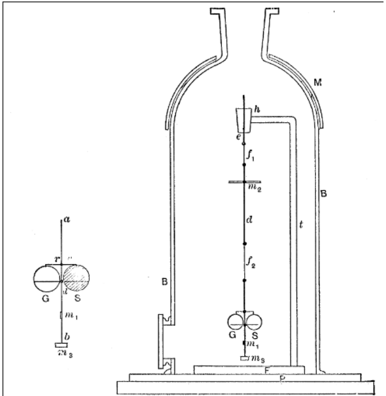
Pressure of Light I

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)

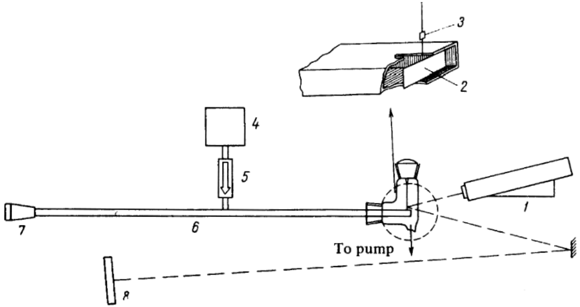
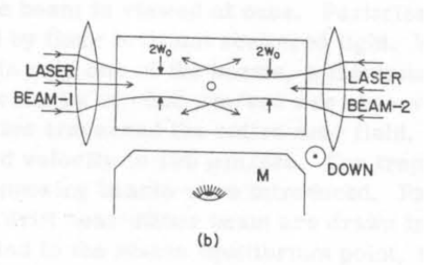


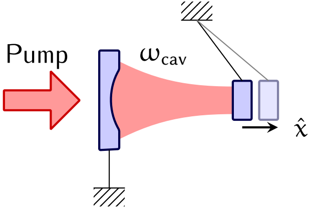
FIG. 1. Schematic diagram of the experimental arrangement: 1—laser, 2—plate-oscillator, 3—mirror, 4—magnetron, 5—ferrite valve, 6—resonator, 7—mobile piston, 8—photographic film.

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

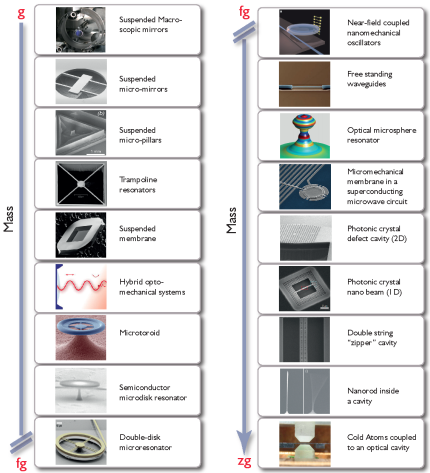
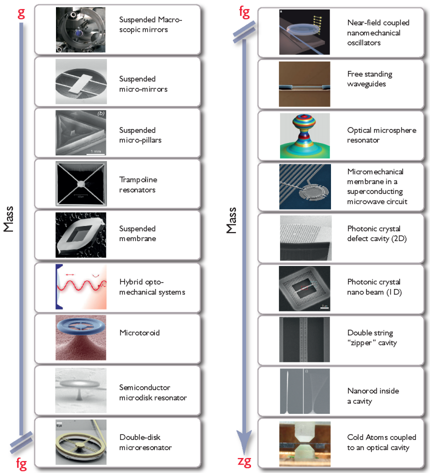


Figure source: [1]

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

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

Experimental Realizations



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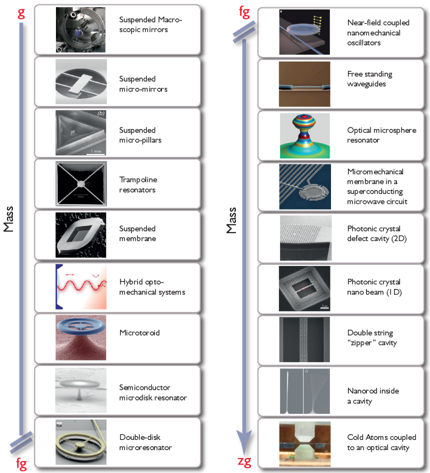

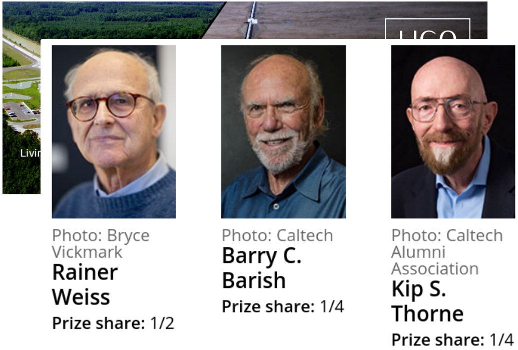

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Experimental Realizations

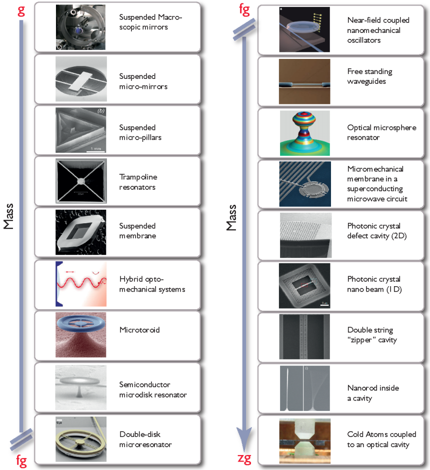
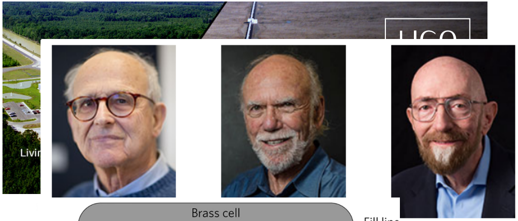


Figure source: [1]



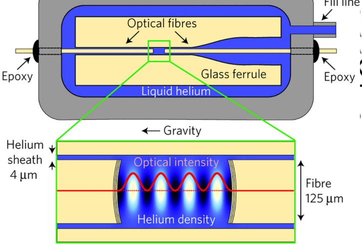


Figure source: [2]

[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

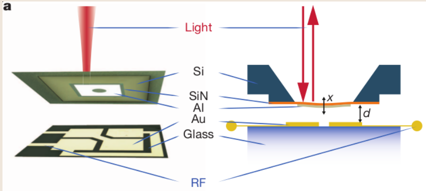


Figure source [3]

Nonlinear Mechanical Potential

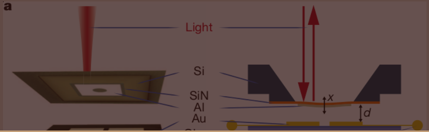
Strong Coupling (High Cooperativity)

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

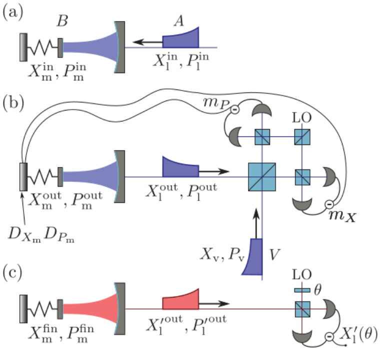
Strong Coupling (High Cooperativity)

Long Coherence Time

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

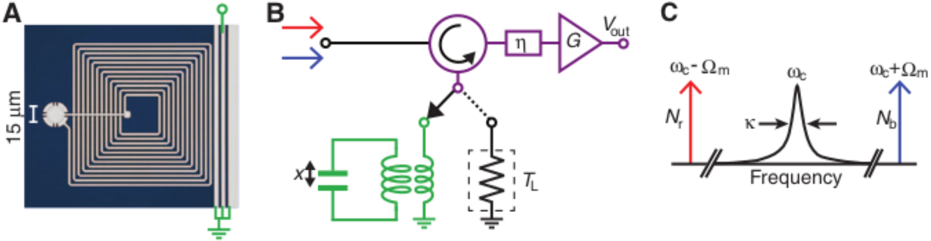
Pulsed Optomechanical Entanglement I

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

Optics

Standard quantization of the cavity field

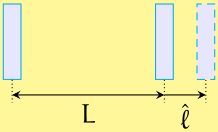
$$\mathbf{E}(\mathbf{r},t) = \sum_p \sum_k \mathbf{e}_p u_k(\mathbf{r}) a_k(t)$$

Mechanics

Displacement field

$$\mathbf{u}(\mathbf{r},t) = \sum_n u_n(\mathbf{r}) x_n(t)$$

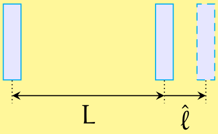
The Hamiltonian



a — optical mode
b — mechanical mode

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

The Hamiltonian



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

Modulation of the cavity frequency

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

The Hamiltonian

$$
\begin{aligned}
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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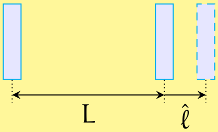

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$$\hat{\ell} = \sqrt{\frac{\hbar}{2m\omega_m}}(b + b^\dagger)$$

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

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

The Hamiltonian

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

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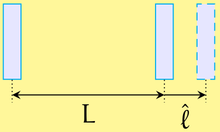
In dimensionless units

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

With the single-photon coupling strength

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



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

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

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

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

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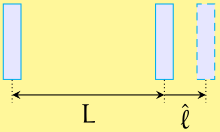
With $m = 10$ ng, $\omega_m = 1$ MHz, $L = 10$ mm,

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



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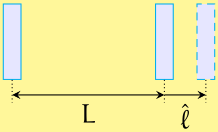

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With $m = 10$ ng, $\omega_m = 1$ MHz, $L = 10$ mm,

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

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

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

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Blank frame

Blank frame to center