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Condensed Matter Summer School, 2018

Day 1: Quantum optomechanics

Day 2: Quantum transduction

Day 3: Ultracold atoms from a qubit perspective
Day 1: Quantum optomechanics

Day 2: Quantum transduction

Day 3: Ultracold atoms from a qubit perspective
Day 1: Quantum optomechanics – quantum limits to continuous displacement detection

Day 2: Quantum transduction – conversion from microwave (superconducting qubits) to optical photons (transmission domain)
Machinery is that of weak nonlinearity / gaussian states
Useful to understanding from perspective of quantum metrology, transducers

Day 3: Ultracold atoms from a qubit perspective – interfering and entangling bosonic atoms
Single atom ‘sources’
Overview of field of control of individual neutral atoms
Some examples of creating Bell states
Quantum optomechanics outline

Basic interaction and cooling of moving mirror in cavity / interferometer – example of more general machinery

Example optomechanics experiments

Continuous displacement detection and squeezing – an old problem

Quantum noise and measurement and amplifiers

Some of our experiments

Will lead into tomorrow – can we optically read out the force of a single microwave photon? – modern problem of quantum transduction from superconducting qubits
Light controls micromechanical motion

Micromechanical motion controls light

Effectively moving mirrors

Moving capacitor plate

Piezoelectrics
\[ F = \hbar c \hat{n} \quad \Rightarrow \quad \frac{d\omega_c}{dx} \]
\[ \hat{n} = \hat{a}^\dagger \hat{a} \]
\[ \hat{a} \rightarrow \text{cavity mode} \]

\[ H = \hbar \omega_c \hat{a}^\dagger \hat{a} + \hbar \omega_m \hat{b}^\dagger \hat{b} + \hbar g \hat{a}^\dagger \hat{a} (\hat{b}^\dagger + \hat{b}) \]
\[ \Rightarrow \quad \frac{d\omega_c}{dx} x_{2p} \]
\[ \hat{b} \rightarrow \text{mechanical mode} \]

\[ \hat{a} \rightarrow \alpha + \hat{\xi} \]
\[ \alpha \text{ stemming from large } \alpha \text{ in} \]
Optomechanical interaction

\[ \hat{H}_{\text{int}} = \hbar g (\hat{\alpha} + S \hat{a})^\dagger (\hat{\alpha} + S \hat{a}) (\hat{b} + \hat{b}^\dagger) \]

\[ = \hbar g k \lambda^2 (\hat{b} + \hat{b}^\dagger) + \hbar g (\alpha^* S \hat{a} + \alpha S \hat{a}^\dagger)(\hat{b} + \hat{b}^\dagger) \]

\[ + \hbar g S \hat{a} \delta \hat{a}^\dagger (\hat{b} + \hat{b}^\dagger) \]

\[ \text{Smaller by } \alpha \]

\[ \lambda \text{ real valued } \lambda = \sqrt{N} \]

\[ \hat{H}_{\text{int}}^{(\text{lin})} = \hbar g \alpha (S \hat{a} + \delta \hat{a}^\dagger)(\hat{b} + \hat{b}^\dagger) \]

\[ \Delta = \omega_m - \omega_c \]

Red detuned \[ \Delta = -\omega_m \]

\[ \delta \hat{a}^\dagger \hat{b} + S \hat{a} \hat{b}^\dagger \]

Beamsplitter

On resonance \[ \Delta = 0 \]

\[ (\delta \hat{a}^\dagger + S \hat{a}) \hat{x} \]

Interferometer

Blue detuned \[ \Delta = \omega_m \]

\[ \hat{b} \delta \hat{a} + \hat{b}^\dagger \delta \hat{a}^\dagger \]

Two-mode squeezing
Range of size scales
Our optomechanical device

\[ \lambda = 1064 \text{ nm} \]

\[ X_{zp} = \sqrt{\frac{t}{2m \omega_m}} \]

\[ \sim 1 \text{ fm} \]

\[ \gamma_m = 1 \text{ MHz} \]
Resolved sideband cooling

\[ \alpha \propto \frac{1}{1 + (4\omega_m/k)^2} \times (N_{m+1}) \]

\[ \propto N_m \]

\[ \frac{S_{FF}(\omega_m)}{S_{FF}(-\omega_m)} = \frac{N_{m+1}}{N_m} = e^{\frac{k\omega m}{k_B T}} \]
Thermalization rate with mechanical environment

Optical measurement rate / Photon-phonon exchange rate with propagating field

LARGE

\[ \Gamma_{opt} = \frac{4\alpha^2 g^2}{\kappa} \]

\[ \alpha^2 = N \]

Lots of light

\[ g = \chi_{ep} \frac{d\omega_c}{dx} \]

\[ \Gamma_{th} = N_{th} \Gamma_m \]

\[ \Gamma_m = \frac{\omega_m}{Q_m} \]

\[ N_{th} = \frac{R_b T}{\hbar \omega_m} \]

High \( Q_m \)

Cold Bath
Quantum backaction limit of cooling

\[ \bar{n} \approx n_0 \]

\[ \bar{n} \approx 1 \]

\[ \bar{n} \approx n_{ba} \]
Ground-state optomechanical cooling

Data here: R. W. Peterson et al., PRL (2016)
Gravitational wave detection

- Sensitive optical interferometer
- Aims to detect $\sim 10^{-18}$ m
In limit of strong probing

- No longer immutable structure
- Light pressure on mirrors important – radiation pressure
- Vladimir Braginsky, 1970’s – instabilities

![Diagram of a laser, photodetector, test mass, and beamsplitter]
In limit of strong probing

- Effect on signal to noise?
- Will radiation forces combined with fluctuations of light obscure the motion?
Continuous measurement: Round 1

- Back of the envelope calculation (Heisenberg microscope argument)
- Consider free mass limit - time small compared to oscillation period
- To measure passing wave must measure more than once...

Measure to $\Delta x_{\text{meas}}$ @ time $t$

Momentum uncertain to $\Delta p_{\text{perturb}} \geq \frac{\hbar}{2 \Delta x_{\text{meas}}}$

At a later time $\ldots$

$\Delta x(t') = \Delta x(t) + \frac{\hbar(t'-t)}{2m \Delta x(t)} \rightarrow \Delta x_{\text{SQL}} = \sqrt{\frac{2\hbar(t'-t)}{m}}$
Source of backaction: Radiation pressure SN

Quantum-Mechanical Radiation-Pressure-Fluctuations in an Interferometer

Carlton M. Caves

W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125
(Received 29 January 1980)

The interferometers now being developed to detect gravitational waves work by measuring small changes in the positions of free masses. There has been a controversy whether quantum-mechanical radiation-pressure fluctuations disturb this measurement. This Letter resolves the controversy: They do.

Our terminology:
“Radiation pressure shot noise (RPSN)”
Standard quantum limit in continuous detection

\[ S_{xx} \rightarrow \omega \]

\[ S_{xx} \text{ units } m^2/Hz \]

Imprecision \( S_{xx} \)

Backaction force \( S_{FF} \)

\[ \chi_m = \frac{1}{m(\omega^2 - \omega_m^2) + im\gamma_m \omega} \]
Standard quantum limit in continuous detection

SQL on mechanical resonance

Measurement added noise
Ideal and ‘standard’ probe

Mechanical zero-point level

Normalized probe power (p)
Added noise for two-quadrature measurements

\[ X_1 = \frac{1}{2}(a_s + a_s^+) \]
\[ X_2 = \frac{1}{2i}(a_s - a_s^+) \]
\[ [X_1, X_2] = \frac{i}{2} \]

Uncertainty product
\[ \langle \Delta x_1^2 \rangle \langle \Delta x_2^2 \rangle \geq \frac{1}{16} \]

Amplify
\[ Y_1 = \sqrt{G_1} X_1 + F_1 \]
\[ Y_2 = \sqrt{G_2} X_2 + F_2 \]
Also need \([Y_1, Y_2] = \frac{i}{2}\]

Ends up implying
\[ \frac{\langle \Delta Y_1^2 \rangle \langle \Delta Y_2^2 \rangle}{\frac{1}{G_1} + \frac{1}{G_2}} \geq \frac{1}{16} \left( 2 - \frac{1}{\sqrt{G_1 G_2}} \right)^2 \]

Added noise \( A_n = \frac{1}{2} \)

A. A. Clerk, Introduction to quantum noise, measurement, and amplification, RMP (2010)
Experiment: Observation of RPSN

RPSN: Radiation Pressure Shot Noise

Displacement spectral density (units of SQL) vs. measurement strength relative to $P^{SQL}$

In 4 K cryostat

Squeezing of light: Correlations in quantum noise

Radiation pressure shot noise (amplitude of light) drives mechanics, writes back onto cavity (phase of light)

Optomechanical squeezing observed with:
Illustrated guide to broadband detection

Frequency dependence for backaction-limited probe

\[
S_{xx}(\omega) = \frac{\omega - \omega_m}{\Gamma_m/2}
\]
LIGO measurement context

LIGO collaboration, Nature Physics (2011)
Illustrated guide to broadband detection

\[ X_\phi = X_{AM} \cos \phi + X_{PM} \sin \phi \]

QL – quantum limit for two mechanical quadrature measurement
Using ponderomotive squeezing

\[ X_\phi = X_{AM} \cos \phi + X_{PM} \sin \phi \]

\[ \frac{\omega - \omega_m}{\Gamma_m/2} \]

Variational readout
Varied \( \phi \)

\begin{itemize}
  \item back action
  \item zero-point fluctuations
  \item shot-noise
  \item QL
  \item SQL
\end{itemize}

As a function of probe power

\[ X_\phi = X_{AM} \cos \phi + X_{PM} \sin \phi \]

\[ \frac{\omega - \omega_m}{\Gamma_m/2} = 5 \]

\[ S_{xx}(p) \]

\[ \text{normalized probe power} \]

A. A. Clerk, Introduction to quantum noise, measurement, and amplification, RMP (2010)
\[
S_{xx}(\omega) = S_m(\omega) + S_{II} + |\chi_m(\omega)|^2 S_{FF} \\
+ 2 \Re \left[ \chi_m(\omega) S_{IF} \right]
\]

\[
\chi_m(\omega) = \frac{1}{m(\omega^2 - \omega_m^2) + i \Gamma_m \omega}
\]
SQL and off-resonant SQL measurements

Probe damped mechanics with on-cavity-resonance probe

Shot noise limit given finite optical efficiency (35%)

Normalized probe power

$\bar{n} = 1.3$

10 linewidths off resonance

10 linewidths off resonance
SQL and off-resonant SQL measurements

\[
S_{xx} \quad 1 \quad 0.1
\]

\[
2(\omega - \omega_m)/\Gamma \quad -12 \quad -6 \quad 6 \quad 12
\]

\phi = 90
\phi = 45
Idea of variational readout

\[ S_{xx} = \frac{\phi}{\omega_m} \left( \frac{\phi}{\omega_m} \right)^2 \]

\[ \phi = 90^\circ \]
\[ \phi = 45^\circ \]
\[ \phi = 60^\circ \]
\[ \phi = 75^\circ \]
Illustrated guide to broadband detection

L. Buchmann et al., PRL (2016)
Thermal noise – ubiquitous problem in metrology

- Tail grows with material loss (smaller Q)
- Crystalline materials are desired
- We live in a forest of modes at higher frequency

Phononic crystals

Period structures: Phononic crystal
• Control mode structure
• Reduce acoustic energy at lossy boundary

Displacement on membrane

predicted bandgap

Mayer Alegre et al., Optics Express (2011); Yu et al., APL (2014)
Y. Tsaturyan et al., Nature Nanotech (2016); M. Yuan...Steele, APL (2015)
Extreme mechanical properties

Drive membrane and watch energy decay

![Graph showing normalized signal over time with a decay rate of 1 min.](image)

- Frequency: $f = 1.6 \text{ MHz}$
- Quality factor: $Q = 200 \times 10^6$

Corresponding heating rate = 10 quanta/ms

- Temperature: $T = 40 \text{ mK}$

M. Yuan...Steele, APL (2015)
R. Fischer et al., in preparation
The team

Regal group optomechanics team

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