Tue

2 most important assumptions of the Q. Thy

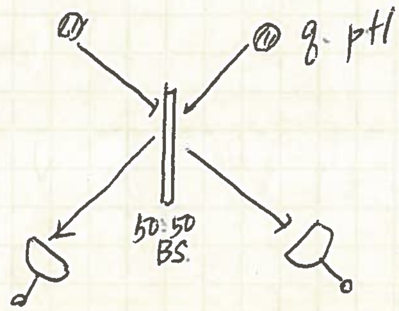
① symmetrization postulate ⇒ "statistical properties of an ptl ensemble @ thermal eq.

② non-commutability of conjugate observables ⇒ "uncertainty product"

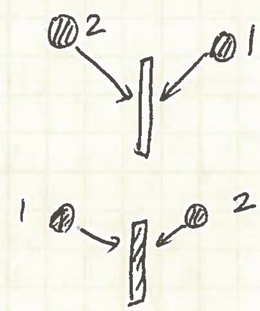
I. Symmetrization Postulate

Quantum Indistinguishability

Suppose an ideal 50%-50% ptl beam splitter. There are two identical q. ptls incident upon the BS, and we measure the output.



collision experiment



Input states $|1,R;2,L\rangle$ ptl 1 at the right input, ptl 2 at the left input

or

$|1,L;2,R\rangle$

Most general input state

$C_0|1,R;2,L\rangle + C_1|1,L;2,R\rangle$ where $|C_0|^2+|C_1|^2=1$ if two states are orthogonal

∴ experimental result dep. on $\underline{C_0 \;\&\; C_1}$, $C_0, C_1 \in \mathbb{C}$

inherent uncertainty/ambiguity to predict the exp. result

∴ Need a fundamental assumption, symmetrization postulate

Statement of the postulate

a physical state of a real system consisting of identical q. ptl is either symmetric or anti-symmetric w.r.t. the permutation of any 2 ptls

symmetric : Boson

anti-sys : fermion

e.g. $\frac{1}{\sqrt{2}}[|1,R;2,L\rangle + |1,L;2,R\rangle]$

$\frac{1}{\sqrt{2}}[|1,R;2,L\rangle - |1,L;2,R\rangle]$

if two states are orthogonal

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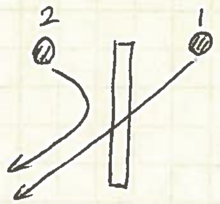
Let's calculate the probability of finding the 2 ptls in the same output port (L)

2-possibilities



or

direct term exchange term

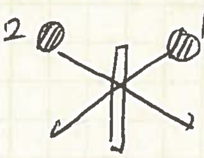
BS scattering matrix $\hat{U} = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ -1 & 1 \end{pmatrix}$ in the basis of 2 transmission modes $\begin{bmatrix} |k_{R\to L}\rangle \\ |k_{L\to R}\rangle \end{bmatrix}$

$$\therefore \left|\langle 1,L;2,L|\,\hat{U}\,\frac{1}{\sqrt{2}}\left[|1,R;2,L\rangle \pm |1,L;2,R\rangle\right]\right|^2$$

$$= \left|\frac{1}{\sqrt{2}}\left(\frac{1}{\sqrt{2}}\times\frac{1}{\sqrt{2}}\right) \pm \frac{1}{\sqrt{2}}\left(\frac{1}{\sqrt{2}}\times\frac{1}{\sqrt{2}}\right)\right|^2 = \begin{cases} \frac{1}{2} & \text{boson : constructive interfere} \\ 0 & \text{fermion : destructive interfere.} \end{cases}$$

$$\left|\langle 1,R;2,R|\,\hat{U}\,\frac{1}{\sqrt{2}}\left[|1,R;2,L\rangle \pm |1,L;2,R\rangle\right]\right|^2 = \begin{cases} \frac{1}{2} & \text{boson} \\ 0 & \text{fermion.} \end{cases} \quad \underline{\text{bunching}}$$

How about the probability of finding $|1,L;2,R\rangle$?



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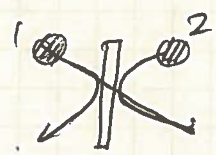


direct term exchange term

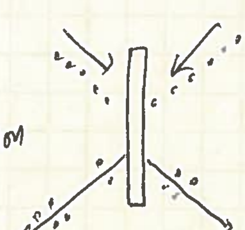
$$\left|\langle 1,L;2,R|\,\hat{U}\,\frac{1}{\sqrt{2}}\left[|1,R;2,L\rangle \pm |1,L;2,R\rangle\right]\right|^2 = \begin{cases} 0 & \text{boson : destructive} \\ \frac{1}{2} & \text{fermion : constructive} \end{cases}$$

anti bunching

$$\left|\langle 1,R;2,L|\,\hat{U}\,\frac{1}{\sqrt{2}}\left[|1,R;2,L\rangle \pm |1,L;2,R\rangle\right]\right|^2 = \begin{cases} 0 & \text{boson} \\ \frac{1}{2} & \text{fermion.} \end{cases}$$

$\therefore$

boson



bunching "Bose-einstein condensation"

fermion

anti-bunching. "Pauli exclusion principle"

$|\psi\rangle_{out} = \frac{1}{\sqrt{2}}\left[|1,R;2,R\rangle - |1,L;2,L\rangle\right]$ $|\psi\rangle_{out} = \frac{1}{\sqrt{2}}\left[|1,R;2,L\rangle - |1,L;2,R\rangle\right]$

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Symmetrization postulate for spin $\frac{1}{2}$ particles

Suppose 2 spin-$\frac{1}{2}$ ptls are incident upon the 50-50 BS.

Assume that the scattering matrix of the BS is assume to be spin-independent.

If the 2-ptls are in spin triplet (symmetric spin states),

the orbital states are

symmetric for bosons
antisym. for fermions

for the overall-state symmetrization

Boson: $\frac{1}{\sqrt{2}}[|R\rangle_1|L\rangle_2 + |L\rangle_1|R\rangle_2] \otimes \begin{cases} |\uparrow\rangle_1|\uparrow\rangle_2 \\ |\downarrow\rangle_1|\downarrow\rangle_2 \\ \frac{1}{\sqrt{2}}[|\uparrow\rangle_1|\downarrow\rangle_2 + |\downarrow\rangle_1|\uparrow\rangle_2\rangle \end{cases}$

$\Downarrow$ short notation for $|1,R;2,L\rangle$

fermions: $\frac{1}{\sqrt{2}}[|R\rangle_1|L\rangle_2 - |L\rangle_1|R\rangle_2] \otimes \begin{cases} |\uparrow\rangle_1|\uparrow\rangle_2 \\ |\downarrow\rangle_1|\downarrow\rangle_2 \\ \frac{1}{\sqrt{2}}[|\uparrow\rangle_1|\downarrow\rangle_2 + |\downarrow\rangle_1|\uparrow\rangle_2\rangle \end{cases}$

The outputs are same as the spinless cases

If 2 ptl are in spin-singlet (anti-symmetric spin. state)

Boson: $\frac{1}{\sqrt{2}}[|R\rangle_1|L\rangle_2 - |L\rangle_1|R\rangle_2] \otimes \frac{1}{\sqrt{2}}[|\uparrow\rangle_1|\downarrow\rangle_2 - |\downarrow\rangle_1|\uparrow\rangle_2]$

fermion: $\frac{1}{\sqrt{2}}[|R\rangle_1|L\rangle_2 + |L\rangle_1|R\rangle_2] \otimes \frac{1}{\sqrt{2}}[|\uparrow\rangle_1|\downarrow\rangle_2 - |\downarrow\rangle_1|\uparrow\rangle_2]$

Now the outputs are.

bosons feature (1, 1) output

fermions (0, 2) or (2, 0) output.

This means that 2 spin-$\frac{1}{2}$ fermions can occupy the same state.

Conversely, if 2-identical fermions occupy the same orbital state,

the spin state has to be always a spin-singlet!

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II. Non-Commutability Postulate of Quantum Mechanics
fundamental postulate

$\boxed{\text{• Heisenberg uncertainty principle.}}$

in QM, a pair of conjugate observables must satisfy the following commutation relation

$$[\underset{\text{position}}{\hat{q}}, \underset{\text{momentum}}{\hat{p}}] = \hat{q}\hat{p} - \hat{p}\hat{q} = i\hbar$$ ← p. & q do not commute.

cf) in classical mechanics $[q, p] = 0$.

Introducing the fluctuation operators

$$\Delta q = \hat{q} - \langle q \rangle, \quad \Delta p = \hat{p} - \langle p \rangle$$

ensemble-averaged values $\langle q \rangle, \langle p \rangle \in \mathbb{R}$
$\because$ q & p: observables

$$[\Delta q, \Delta p] = [\hat{q} - \langle q \rangle, \hat{p} - \langle p \rangle] = [\hat{q}, \hat{p}] = i\hbar$$

Let's calculate the uncertainty product for Δq and Δp.

Suppose $|\varphi\rangle = \Delta q|\psi\rangle$, $|\chi\rangle = \Delta p|\psi\rangle$.

Using the Schwartz inequality,

$$\langle \varphi|\varphi\rangle\langle \chi|\chi\rangle \ge |\langle \varphi|\chi\rangle|^2$$ where $|\psi\rangle$ = a ket vector representing a quantum state of a given ph sy.

the equality holds if and only if $|\varphi\rangle = c_1|\chi\rangle$ where $c_1 \in \mathbb{C}$

$$\langle \Delta q^2 \rangle \langle \Delta p^2 \rangle \ge |\langle \Delta q \Delta p \rangle|^2$$ where,

$$\Delta q \Delta p = \frac{1}{2}(\Delta q \Delta p + \Delta p \Delta q) + \frac{1}{2}(\Delta q \Delta p - \Delta p \Delta q)$$
$$= \frac{1}{2}(\Delta q \Delta p + \Delta p \Delta q) + \frac{i}{2}\hbar$$

$$\langle \Delta q^2 \rangle \langle \Delta p^2 \rangle \ge \frac{1}{4}|\underbrace{\langle \Delta q \Delta p + \Delta p \Delta q \rangle}_{\Downarrow \text{ real number}} + i\hbar|^2$$

$\because$ it's an ensemble-averaged value

$$\therefore \langle \Delta q^2 \rangle \langle \Delta p^2 \rangle \ge \frac{\hbar^2}{4}$$ Heisenberg uncertainty principle.

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$\boxed{\text{• Minimum uncertainty wavepacket}}$

For the equality $\langle \Delta q^2 \rangle \langle \Delta p^2 \rangle = \frac{\hbar^2}{4}$

$$\Delta q |\psi\rangle = c_1 \Delta p |\psi\rangle$$
$$\langle \psi | \Delta q \Delta p + \Delta p \Delta q | \psi \rangle$$

$|\psi\rangle$ has to satisfy these conditions simultaneously.

$$\langle \psi | \Delta q \Delta q | \psi \rangle = \langle \psi | c_1^* c_1 \Delta p^2 | \psi \rangle$$

$$\langle \psi | c_1^* \Delta p^2 | \psi \rangle + \langle \psi | c_1 \Delta p^2 | \psi \rangle = \langle \psi | \Delta p^2 | \psi \rangle (c_1 + c_1^*) \overset{?}{=} 0$$

If $|\psi\rangle$ is not an eigenstate of $\hat{p}$, $\langle \Delta p^2 \rangle \neq 0$ so that $\underline{c_1}$ must be a pure imag. #.

If $c_1 = -ic_2$, $c_2 \in \mathbb{R}$,

$$(\hat{q} - \langle q \rangle)|\psi\rangle = -ic_2 (\hat{p} - \langle p \rangle)|\psi\rangle$$

If we project an eigen-bra $\langle q' |$,

$\boxed{\langle q' | \psi \rangle = \psi(q') \text{ wavefn}}$

$$(\hat{q}' - \langle q \rangle) \langle q' | \psi \rangle = (\hat{q}' - \langle q \rangle) \psi(q') = -ic_2 \left(\frac{\hbar}{i} \frac{\partial}{\partial q'} - \langle p \rangle \right) \psi(q')$$

$$\hat{p} = \frac{\hbar}{i} \frac{\partial}{\partial x}$$

The solution is given by

$$\psi(q') = c_3 \exp\left[\frac{i}{\hbar} \langle p \rangle q' - \frac{1}{2\hbar c_2} (q' - \langle q \rangle)^2 \right]$$

c_3: a constant of integration

$$\int_{-\infty}^{\infty} |\psi(q')|^2 dq' = 1$$

$$\int_{-\infty}^{\infty} (q' - \langle q \rangle)^2 |\psi(q')|^2 dq' = \langle \Delta q^2 \rangle$$

$$\therefore c_2 = \frac{2\langle \Delta q^2 \rangle}{\hbar}, \quad |c_3|^2 = \frac{1}{\sqrt{2\pi \langle \Delta q^2 \rangle}}$$

Gaussian wavepacket

$$\therefore \text{w/o loss of generality}, \quad \psi(q') = (2\pi \langle \Delta q^2 \rangle)^{-\frac{1}{4}} \exp\left[\frac{i}{\hbar} \langle p \rangle q' - \frac{(q' - \langle q \rangle)^2}{4\langle \Delta q^2 \rangle} \right]$$

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p' – representation of the Schrödinger wavefn by the F.T.

$$\varphi(p') \equiv \langle p'|\psi\rangle = \frac{1}{\sqrt{2\pi\hbar}}\int_{-\infty}^{\infty} \exp\left(-\frac{i}{\hbar}p'q'\right)\psi(q')\,dq'$$

$$= \left(2\pi\langle\Delta p^2\rangle\right)^{-\frac{1}{4}} \exp\left[-\frac{i}{\hbar}\langle q\rangle(p'-\langle p\rangle - \frac{(p'\langle p\rangle)^2}{4\langle\Delta p^2\rangle}\right]$$

where $\langle\Delta p^2\rangle = \dfrac{\hbar^2}{4\langle\Delta q^2\rangle}$

If we rewrite $(\hat{q}-\langle q\rangle)|\psi\rangle = -ic_2(\hat{p}-\langle p\rangle)|\psi\rangle$

$$(\hat{q}+ic_2\hat{p})|\psi\rangle = (\langle q\rangle + ic_2\langle p\rangle)|\psi\rangle$$

$$\boxed{(e^r\hat{q}+ie^{-r}\hat{p})|\psi\rangle = (e^r\langle q\rangle + ie^{-r}\langle p\rangle)|\psi\rangle}$$ ✓

where a new parameter is defined by $c_2 = e^{-2r}$.

The min. uncertainty state $|\psi\rangle$ is an eigenstate of a "non-Hermitian" operator, $\boxed{e^r\hat{q}+ie^{-r}\hat{p}}$ w/ a c-# eigenvalue $\boxed{e^r\langle q\rangle+ie^{-r}\langle p\rangle}$

- **Coherent state and squeezed state**

Consider a mechanical harmonic oscillator.

$$H = \frac{p^2}{2m} + \frac{1}{2}kq^2 \quad \leftarrow \text{total energy of the system}$$

$$\omega = \sqrt{\frac{k}{m}} \quad \leftarrow \text{oscillation freq.}$$

the minimum uncertainty state $\Leftarrow$ the eigenstate of the non-Hermitian operator

$$\boxed{e^r\hat{q}+ie^{-r}\hat{p}}$$

$$\therefore \langle\Delta q^2\rangle = \frac{\hbar}{2}e^{-2r}$$

$$\langle\Delta p^2\rangle = \frac{\hbar}{2}e^{2r}$$

pg 5. $\langle\Delta q^2\rangle = \frac{\hbar}{2}c_2 = \frac{\hbar}{2}e^{-2r}$ ✓

$$\langle\Delta p^2\rangle = \frac{\hbar^2}{4\langle\Delta q^2\rangle} = \frac{\hbar^2}{4\cdot\frac{\hbar}{2}e^{-2r}} = \frac{\hbar}{2}e^{2r}$$ ✓

"r" determines the noise distribution between q and p w/n $\langle\Delta q^2\rangle\langle\Delta p^2\rangle = \frac{\hbar^2}{4}$

↑ "squeezing parameter"

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Expressing $\hat{p}$, $\hat{q}$ in terms of the annihilation and creation operators $\hat{a}$ & $\hat{a}^+$.

$$\hat{q} = \sqrt{\frac{\hbar}{2m\omega}}\,(\hat{a}+\hat{a}^+)$$

$$\hat{p} = \frac{1}{i}\sqrt{\frac{\hbar m\omega}{2}}\,(\hat{a}-\hat{a}^+)$$

∴ We introduce 2-quadrature (amplitude) parameters a_1 & a_2

$$a_1 = \frac{1}{2}(\hat{a}+\hat{a}^+) = \sqrt{\frac{m\omega}{2\hbar}}\,\hat{q}$$

$$a_2 = \frac{1}{2i}(\hat{a}-\hat{a}^+) = \sqrt{\frac{1}{2\hbar m\omega}}\,\hat{p}$$

⇒ New commutator relation

$$\boxed{\begin{aligned}&[a_1, a_2] = \frac{i}{2}\\ &\langle \Delta a_1^2\rangle\langle\Delta a_2^2\rangle \geq \frac{1}{16}\end{aligned}}$$

& the min. uncertainty state = the eigenstate of the operator

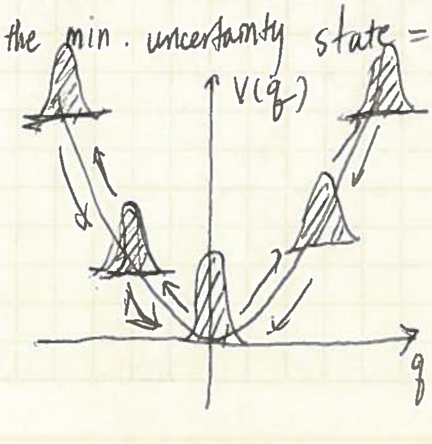
$$e^r\hat{a}_1 + ie^{-r}\hat{a}_2 \quad \&$$

$$\langle\Delta\hat{a}_1^2\rangle = \frac{1}{4}e^{-2r}, \quad \langle\Delta\hat{a}_2^2\rangle = \frac{1}{4}e^{2r}$$

① $r=0$. $\langle\Delta\hat{a}_1^2\rangle = \frac{1}{4}$ $\langle\Delta\hat{a}_2^2\rangle = \frac{1}{4}$

$\longrightarrow$ $e^r\hat{a}_1 + ie^{-r}\hat{a}_2 = \hat{a}_1 + i\hat{a}_2 = \frac{1}{2}(\hat{a}+\hat{a}^+) + \frac{i}{2i}(\hat{a}-\hat{a}^+) = \hat{a}$

$\longrightarrow$ the min. uncertainty state = coherent state



same-width wave ~~package~~ packet

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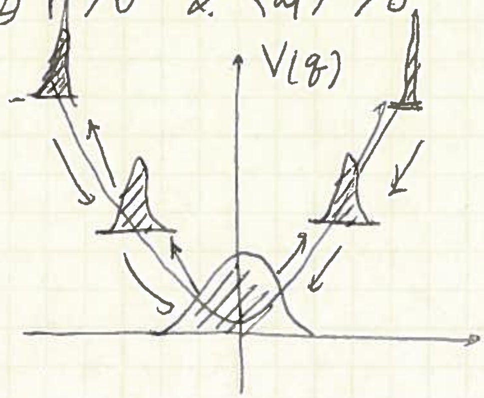
② $r > 0$ & $\langle a_1 \rangle > 0$

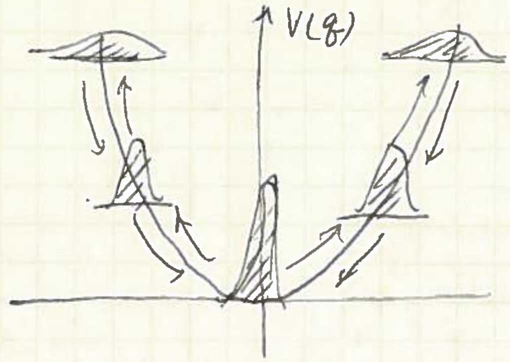


amplitude squeezed state

↓

the quantum uncertainty is min. when an amplitude is measured

③ $r < 0$ & $\langle a_1 \rangle > 0$



phase-squeezed state

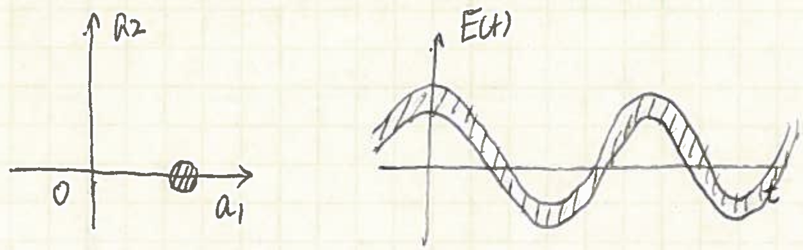
↓

the quantum uncertainty is min. when a phase is min.

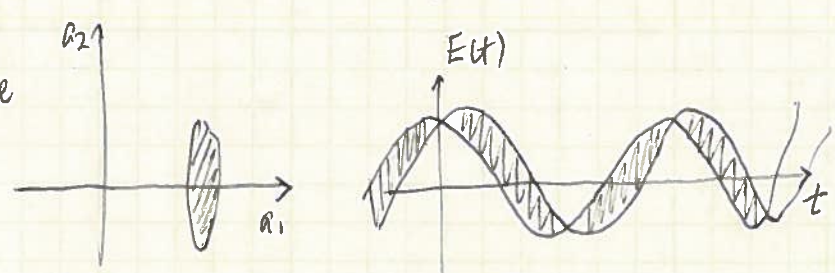
The pulsating uncertainties of the normalized position

$$\langle \Delta a_1^2 \rangle = \frac{m\omega}{2\hbar} \langle \Delta q^2 \rangle$$

coherent state

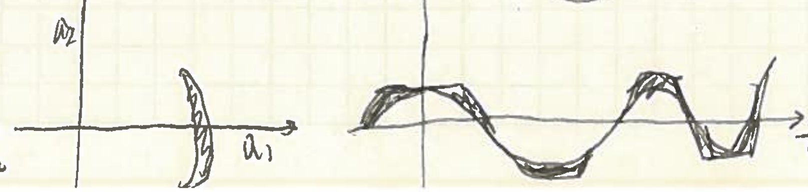


amplitude squeezed state



phase squeezed state

number-phase squeezed state



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· Quantum Noise & thermal noise of a simple HO (harmonic oscillator)

Suppose a HO is at thermal eq.

According to the equipartition thm,

the energy associated with the position q and momentum p are independently given by $\frac{1}{2}k_B\Theta$

Taking into the quantization effect, namely, the energy is quantized in $\hbar\omega$,

the thermal energy $E_t = \hbar\omega\bar{n} = \hbar\omega \cdot \frac{1}{e^{\hbar\omega/k_B\Theta}-1}$

$\bar{n}$ = the eq. photon statistics at a temp. Θ

① when $\hbar\omega \ll k_B\Theta$ ⇒ quantization effect is not important → thermal noise

$E_t \longrightarrow \underline{\underline{k_B\Theta}}$ $\quad \hbar\omega \cdot \frac{1}{1+\frac{\hbar\omega}{k_B\Theta}-1} \approx k_B\Theta$

expected result : $\frac{k_B\Theta}{2} + \frac{k_B\Theta}{2} = k_B\Theta$

② when $\hbar\omega \gg k_B\Theta$ (zero-temp. limit) → "quantum noise.

$E_t \longrightarrow 0$ is this correct? <u>NO</u>

even at $\Theta = 0$, the uncertainty principle <u>requires</u> the zero-point fluctuation vacuum fluctuation in $\hat{p}$ & $\hat{q}$

For the ground state $|0\rangle$,

$\hat{a}|0\rangle = 0 \Rightarrow \therefore |0\rangle$ is a coherent state w/ an eigenvalue of 0
$= 0 \cdot |0\rangle$

$\therefore E_q = \frac{1}{2m}\langle\Delta p^2\rangle + \frac{1}{2}k\langle\Delta q^2\rangle = \hbar\omega(\langle\Delta a_1^2\rangle + \langle\Delta a_2^2\rangle) = \frac{1}{2}\hbar\omega$

$$\therefore E_{Total} = E_t + E_q = \hbar\omega\Big(\underbrace{\frac{1}{e^{\hbar\omega/k_B\Theta}-1}}_{\text{thermal noise}} + \underbrace{\frac{1}{2}}_{\text{quantum noise}}\Big)$$

$\boxed{\text{Quantum Noise of a lossless LC circuit}}$

Consider a lossless LC circuit w/ $\omega_0 = \frac{1}{\sqrt{LC}}$

$i(t)$: the current flowing in L.
$v(t)$: the voltage across C.

$$\Rightarrow \quad C\frac{dv(t)}{dt} = i(t) \qquad L\frac{di(t)}{dt} = -v(t)$$

Introducing the normalized voltage & normalized current

$$q(t) = Cv(t), \qquad p(t) = Li(t)$$

$$\frac{dq(t)}{dt} = \frac{p(t)}{L} \qquad \frac{dp(t)}{dt} = -\frac{q(t)}{C}$$

The total energy stored on the LC circuit is

$$H = \frac{1}{2}Li^2 + \frac{1}{2}Cv^2 = \frac{p^2}{2L} + \frac{q^2}{2C}$$

Taking the analogy w/ a mechanical HO.

$$L \leftrightarrow m$$
$$C \leftrightarrow \frac{1}{k}$$

$$\therefore \frac{dq}{dt} = \frac{\partial H}{\partial p} = \frac{p}{L}, \quad \frac{dp}{dt} = -\frac{\partial H}{\partial q} = -\frac{1}{C}q \leftarrow \text{from classical Hamiltonian}$$

$\therefore q, p$ are a pair of conjugate observables

<u>QM</u>
$$\begin{cases} [\hat{q}, \hat{p}] = i\hbar, & \hat{q}, \hat{p} : \text{q. operators} \\ \langle \Delta q^2 \rangle \langle \Delta p^2 \rangle \geq \frac{\hbar^2}{4} \end{cases}$$

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w/ the non-Hermitian creation ($\hat{a}^\dagger$) and annihilation ($\hat{a}$) operators for a circuit photon,

$$\hat{a} = \frac{1}{\sqrt{2\hbar\omega_0 L}}(\omega_0 L\hat{q} + i\hat{p})$$

$$\hat{a}^\dagger = \frac{1}{\sqrt{2\hbar\omega_0 L}}(\omega_0 L\hat{q} - i\hat{p})$$

$$H = \hbar\omega_0\left(\hat{a}^\dagger a + \frac{1}{2}\right) \qquad [\hat{a}, \hat{a}^\dagger] = 1$$

$\exists$ a vacuum state = an excited LC circuit's QM state

$$\underline{\hat{a}|0\rangle = 0} \qquad \langle 0|a^\dagger = 0,\ a^\dagger|0\rangle = |1\rangle$$

notation for the vacuum state $\rightarrow$ $\bar{q} \equiv \langle 0|\hat{q}|0\rangle = 0 \qquad \hat{q} = \sqrt{\frac{\hbar\omega_0 C}{2}}(\hat{a}^\dagger + a) = 0$

$$\overline{q^2} \equiv \langle 0|\hat{q}^2|0\rangle = \langle 0|\frac{\hbar\omega_0 C}{2}(\hat{a}^{\dagger 2} + a^2 + a^\dagger a + a a^\dagger)|0\rangle$$

$$= \frac{\hbar\omega_0}{2}C$$

$$\bar{p} \equiv \langle 0|\hat{p}|0\rangle = 0 \qquad \hat{p} = i\sqrt{\frac{\hbar\omega_0 L}{2}}(\hat{a}^\dagger - \hat{a})$$

$$\overline{p^2} \equiv \langle 0|\hat{p}^2|0\rangle = \langle 0|\frac{\hbar\omega_0 L}{2}(-\hat{a}^{\dagger 2} - \hat{a}^2 + \hat{a}^\dagger\hat{a} + \hat{a}\hat{a}^\dagger)|0\rangle = \frac{\hbar\omega_0}{2}L$$

$$\overline{\Delta q^2} = \overline{q^2} - \bar{q}^2 = \frac{\hbar\omega_0}{2}C \qquad \therefore \overline{\Delta q^2}\,\overline{\Delta p^2} = \frac{\hbar^2}{4} \ \therefore \text{min. uncertainty}$$

$$\overline{\Delta p^2} = \overline{p^2} - \bar{p}^2 = \frac{\hbar\omega_0}{2}L$$

$$\langle 0|H|0\rangle = \frac{\hbar\omega_0}{2} \Leftarrow \text{zero-point fluctuation}$$

full quantum mechanical expression for an open-circuit voltage power spectral density

$$S_V(\omega) = 2\hbar\omega R \coth\left(\frac{\hbar\omega}{2k_B\Theta}\right)$$

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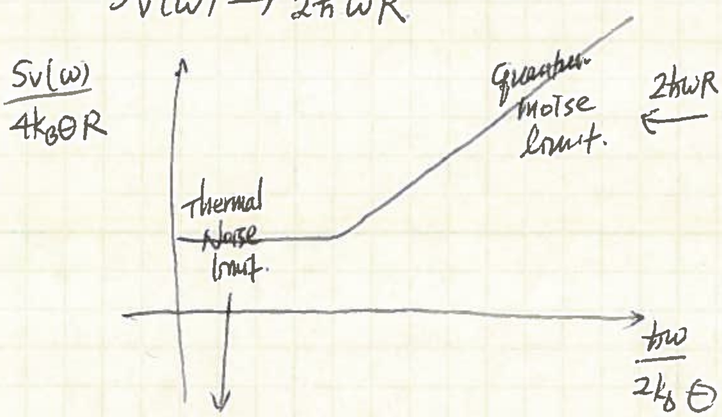
$$S_V(\omega) = 2\hbar\omega R \coth\left(\frac{\hbar\omega}{2k_B\Theta}\right)$$ generalized Nyquist formula

① $\hbar\omega \ll k_B\Theta$ high temp. limit

$$S_V(\omega) \to 4k_B\Theta R$$

② $\hbar\omega \gg k_B\Theta$ low temp limit

$$S_V(\omega) \to 2\hbar\omega R$$



← virtual fluctuation energy
cannot directly be measured
indirectly measured
by a form of photon shot noise
or a mechanical Casimir force

"real fluctuation" energy
intrinsic noise
directly measurable