Regular photodiodes are based on photoelectric effect:
The absorption of a single photon releases a single electron, thus a measured photocurrent is phoportional to the photon flux.

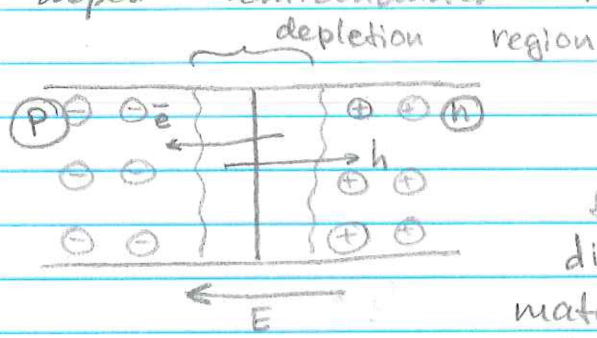
$$I_e = e \cdot (\text{photon flux}) = e \cdot \frac{P_{light}}{\hbar\omega} \quad \text{ideal case}$$

Realistically $I_e = \eta \frac{e}{\hbar\omega} P_{light}$

$$\eta = \frac{N_{electrons}}{N_{photons}} \quad \text{quantum efficiency}$$

Depends on photon wavelengh, losses in the detector, etc.

General principle of the photodetector:
p-n or p-i-n junction
a connection b/w positively and negatively doped semiconductor materials



In equilibrium, free electrons tend to diffuse into p-doped material, and the holes drift into the n-doped material, creating a depletion region at a junction. The electric field created by unbalanced positive and negative ions acts like a barrier to prevent other free carrier from moving across the junction — no conductivity.

Detection of quantum states of light

How to distinguish a coherent state from squeezed state?

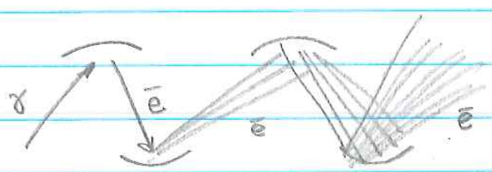
Option 1: photon statistics

$|\psi\rangle = \sum c_n |n\rangle$

photon number resolving detector

Will provide probability distribution for photon number states p_n (not a complete state information, since c_n are complex numbers)

However, a high efficiency photon counting is necessary.
Up until a few years ago → no photon number resolving capability
Avalanch photodetectors



Initial photoelectron is accelerated to the next plate in a high-voltage field, kicking out more electrons at each plate, thus creating an "avalanch" – a macroscopically measurable electic pulse.
Drawback – low detection efficiency ($\gtrsim 50\%$)

Recently, scientists develop methods to extract the photon number information for a few-photon pulses

Possible solutions: multi-plexing

Spatial multiplexing

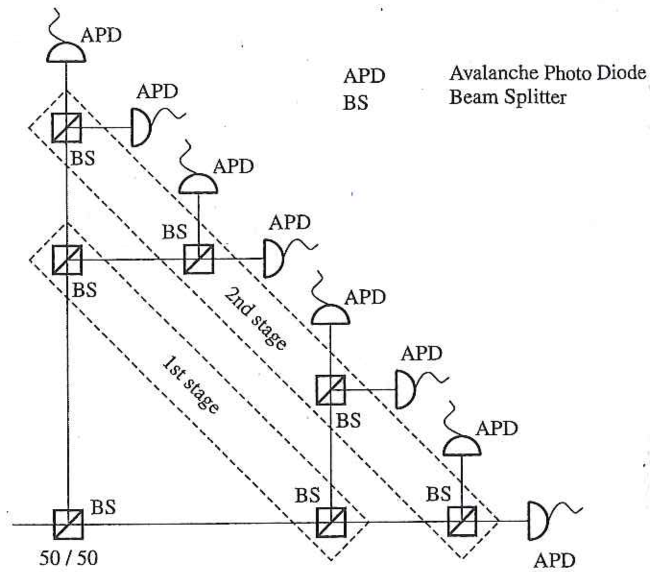


Fig. 5.7. Multiplexed detection schemes. Avalanche photodiodes respond to single photons, but cannot discriminate between one or more detected photons. Multiplexing is a way around this problem. The incident light is distributed to an array of avalanche photodiodes by an arrangement of beam splitters. Each individual detector rarely encounters more than one photon; so the whole device accurately measures the number of photons. Reproduced with permission from Silberhorn (2007).

Temporal multiplexing

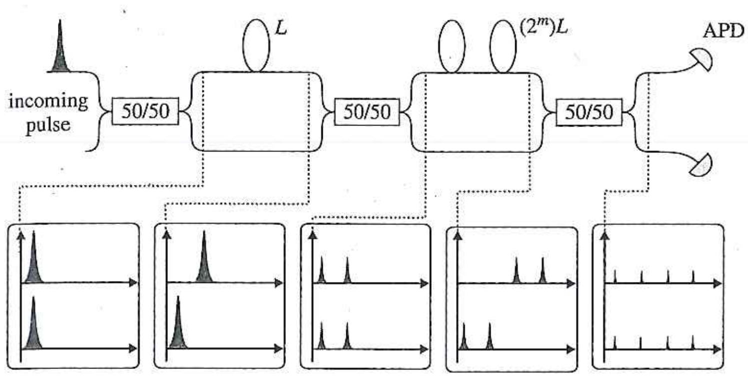
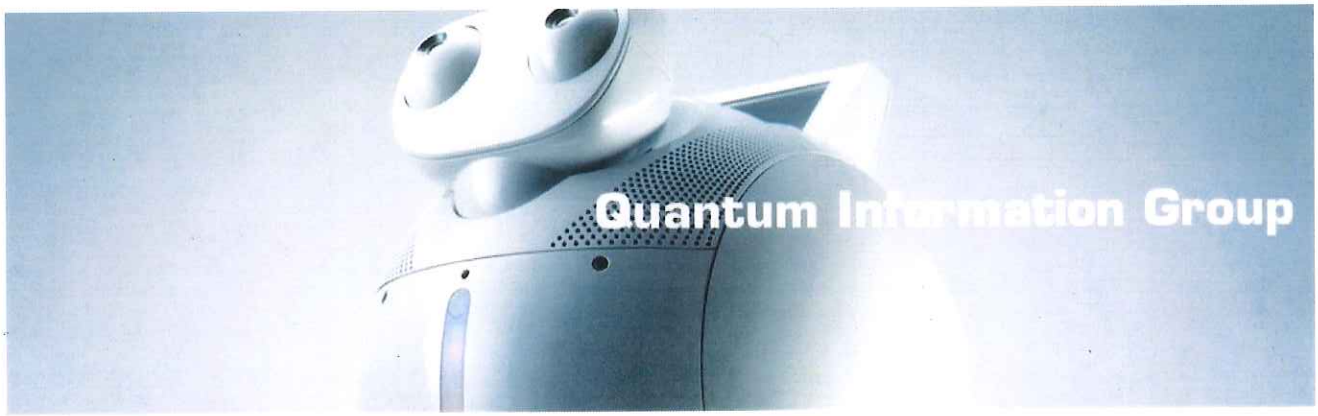
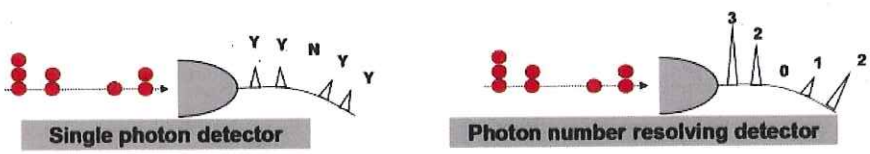


Fig. 5.8. Time-multiplexed detector. The fibre couplers and loops multiplex a pulse of light in time such that two avalanche photodiodes are sufficient for measuring the photon number. This simple scheme replaces the experimentally more complicated one of Fig. 5.7. Reproduced with permission from (Silberhorn, 2007).



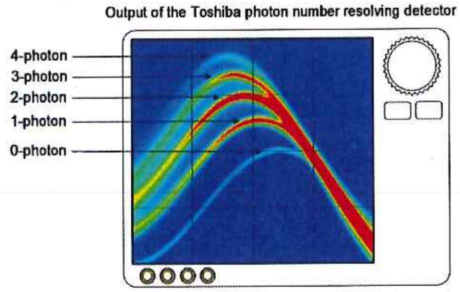
Photon Number Resolving Detector

Single photon detectors which respond equally to one or more incident photons are relatively common. However, for many applications in quantum information technology we require a detector that can distinguish between different numbers of photons. We have realised a practical semiconductor device that can resolve the photon number in each incident light pulse.



A photon number resolving detector can be used to signal the successful operation of photonic gates used in quantum computers, as well as in quantum teleportation. Our detectors could also be used for quantum imaging and tomography, as well as the generation and characterisation of quantum light states. More generally, these detectors can make measurements limited only by the fundamental level of quantum noise, in low-light applications such as biomedical imaging, astronomy and optical range-finding.

Output of the Toshiba photon number resolving detector



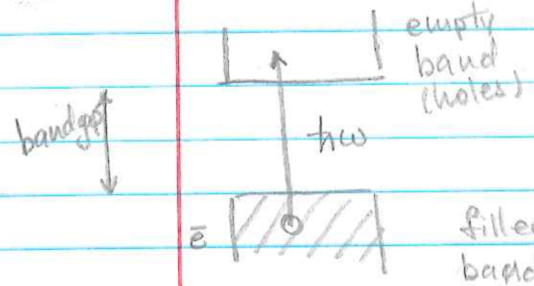
Our detectors exploit small, unsaturated signals from avalanche photodiodes. Avalanche photodiodes are semiconductor devices which allow a single photon to generate a large photocurrent via avalanche multiplication, much like a single snowflake triggering an avalanche of snow. In a single photon detector this charge will grow until it saturates the device, giving a fixed output regardless of the number of incident photons. In our photon number resolving detectors we prevent this from happening by gating the detector, which limits the time for avalanche growth to less than 1 nanosecond. The output signal is proportional to the number of avalanches, which can be clearly discriminated, allowing the photon number to be determined. We have demonstrated this principle in uniform detectors [1,2] as well as using spatially-multiplexed devices, in which avalanches generated in separate zones within a single small-area diode are summed to give the photon number [3].

Because these detectors operate close to room temperature, are compact, scalable and simple to fabricate, our approach is ideal for a wide range of applications in quantum photonics.

Further Information:

[1] B. E. Kardynal, Z. L. Yuan and A. J. Shields, Nature Photonics 2, 425-428 (2008)
[2] O. Thomas, Z. L. Yuan, J. F. Dynes, A. W. Sharpe and A. J. Shields, Appl. Phys. Lett. 97, 031102 (2010)
[3] O. Thomas, Z. L. Yuan and A. J. Shields, Nature Communications 3, 644 (2012)

Energy bands for electrons



Photon, when absorbed, move an electron into an empty high-energy band where it is free to move → electric current

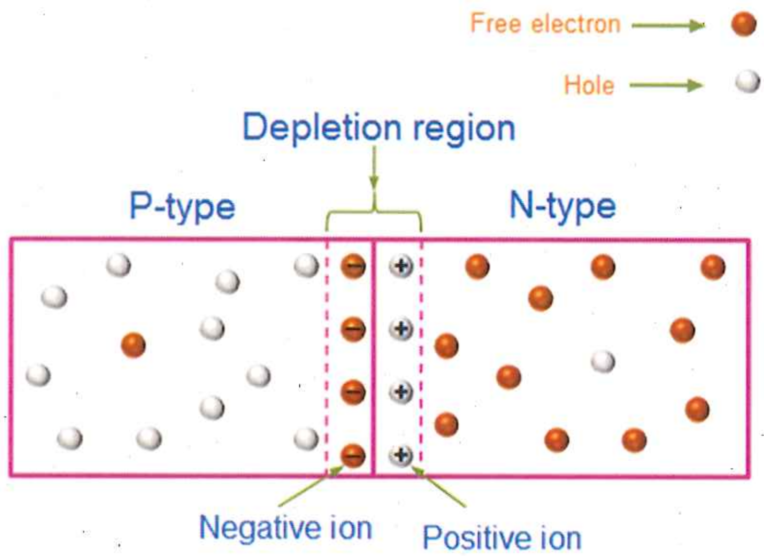
The bandgap of material determines spectral range of operation for a photodiode

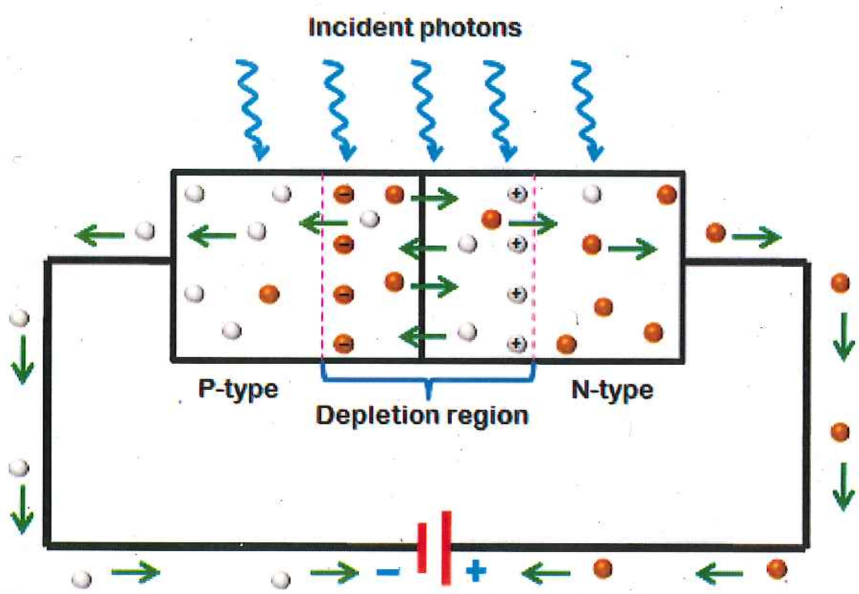
Si : visible (0.4 – 0.9 μm), In-doped – (0.2 – 0.8 μm)
Ge: near-IR (1 – 2 μm)

Si detectors can have very high quantum efficiency (0.8 – 0.9 standard, up to 0.95 – 0.98)

The ultimate quantum efficiency depends on absorption inside material, reflection off all the surfaces, alternative relaxation mechanisms, etc.)

The ability of regular photodetectors to measure weak signals is limited by <u>dark current</u> : thermally-induced electrons, that conduct some current even in the absence of light.

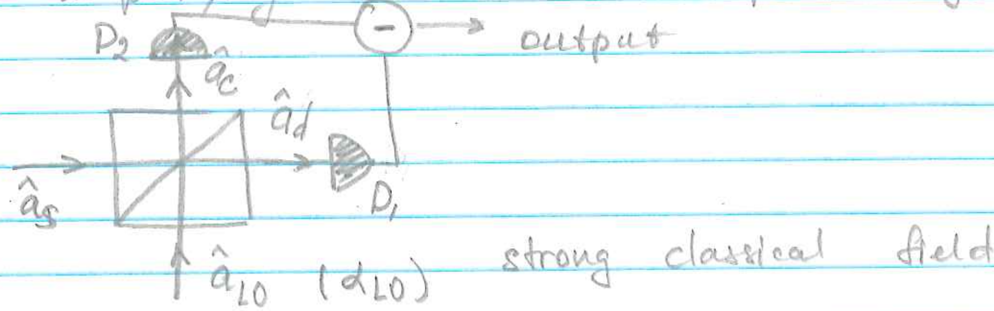




PN Junction photodiode

Balanced homodine detection

We want to take advantage of high quantum efficiency of the conventional detectors, by cleverly "amplifying" our weak optical signal



What we measure: $\Delta\hat{n} = \hat{n}_c - \hat{n}_d = \hat{a}_c^\dagger \hat{a}_c - \hat{a}_d^\dagger \hat{a}_d$

For an ideal 50/50 beam-splitters

$$\hat{a}_c = \frac{1}{\sqrt{2}}(\hat{a}_s + i\hat{a}_{LO})$$

$$\hat{a}_d = \frac{1}{\sqrt{2}}(i\hat{a}_s + \hat{a}_{LO}) = \frac{i}{\sqrt{2}}(\hat{a}_s - i\hat{a}_{LO})$$

$$\hat{n}_c = \hat{a}_c^\dagger \hat{a}_c = \frac{1}{2}(\hat{a}_s^\dagger - i\hat{a}_{LO}^\dagger)(\hat{a}_s + i\hat{a}_{LO}) =$$
$$= \frac{1}{2}(\underline{\hat{a}_{LO}^\dagger \hat{a}_{LO}} + i\hat{a}_s^\dagger \hat{a}_{LO} - i\hat{a}_{LO}^\dagger \hat{a}_s + \hat{a}_s^\dagger \hat{a}_s)$$

largest contribution, puts the signal above the dark noise

$$\hat{n}_d = \hat{a}_d^\dagger \hat{a}_d = \frac{1}{2}(\hat{a}_s^\dagger + i\hat{a}_{LO}^\dagger)(\hat{a}_s - i\hat{a}_{LO}) =$$

$$= \frac{1}{2}(\hat{a}_{LO}^\dagger \hat{a}_{LO} - i\hat{a}_s^\dagger \hat{a}_{LO} + i\hat{a}_{LO}^\dagger \hat{a}_s + \hat{a}_s^\dagger \hat{a}_s)$$

$$\Delta\hat{n} = i(\hat{a}_s^\dagger \hat{a}_{LO} - \hat{a}_{LO}^\dagger \hat{a}_s)$$

Detected current $I_{diff} \propto \langle \Delta n \rangle = i\langle \hat{a}_s^\dagger \hat{a}_{LO} - \hat{a}_{LO}^\dagger \hat{a}_s \rangle$

Again, here we explicitely assume that the local oscillator and the quantum signal are in the identical spatial and temporal modes, since we consider that after the beam-splitter we <u>cannot</u> distinguish which channal the photons came from

Normally, the local oscillator is a strong coherent state $|\alpha_{LO}\rangle$; and $\alpha_{LO} = |\alpha_{LO}| \cdot e^{i\chi}$

$$\langle a_{LO} \rangle = \alpha_{LO} \qquad \langle a_{LO}^{+} \rangle = \alpha_{LO}^{*}$$

$$\langle \Delta \hat{n} \rangle = i \langle \hat{a}_s^{+} \hat{a}_{LO} - \hat{a}_{LO}^{+} \hat{a}_s \rangle = \langle i |\alpha_{LO}| e^{i\chi} \hat{a}_s^{+} - i|\alpha_{LO}| e^{-i\chi} \hat{a}_s \rangle$$

$$= |\alpha_{LO}| \langle \underbrace{\hat{a}_s e^{-i\theta} + \hat{a}_s^{+} e^{i\theta}}_{2\hat{X}_\theta \text{ quadrature operator}} \rangle \cdot \quad \text{if } \theta = \chi + \pi/2$$

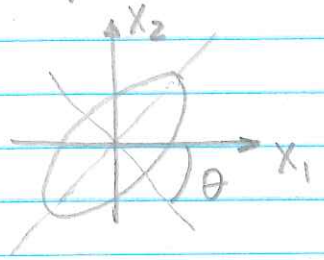
$$\langle \Delta \hat{n} \rangle = 2|\alpha_{LO}| \langle \hat{X}_\theta \rangle$$

Fluctuations of the differential photon flux

$$\langle \Delta \hat{n}^2 \rangle = 4|\alpha_{LO}|^2 \langle \hat{X}_\theta^2 \rangle$$

$$\Delta (\Delta n) = 4|\alpha_{LO}|^2 \langle \Delta \hat{X}_\theta^2 \rangle$$

Squeezed vacuum:



$\langle \hat{X}_1 \rangle = \langle \hat{X}_2 \rangle = 0$

For $\theta = 0$

$\langle \Delta \hat{X}_1 \rangle = \frac{1}{4} e^{-2r}$

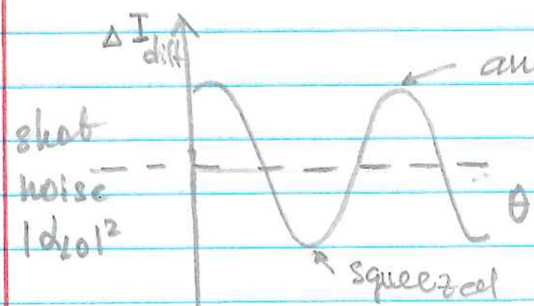
$\langle \Delta \hat{X}_2 \rangle = \frac{1}{4} e^{2r}$

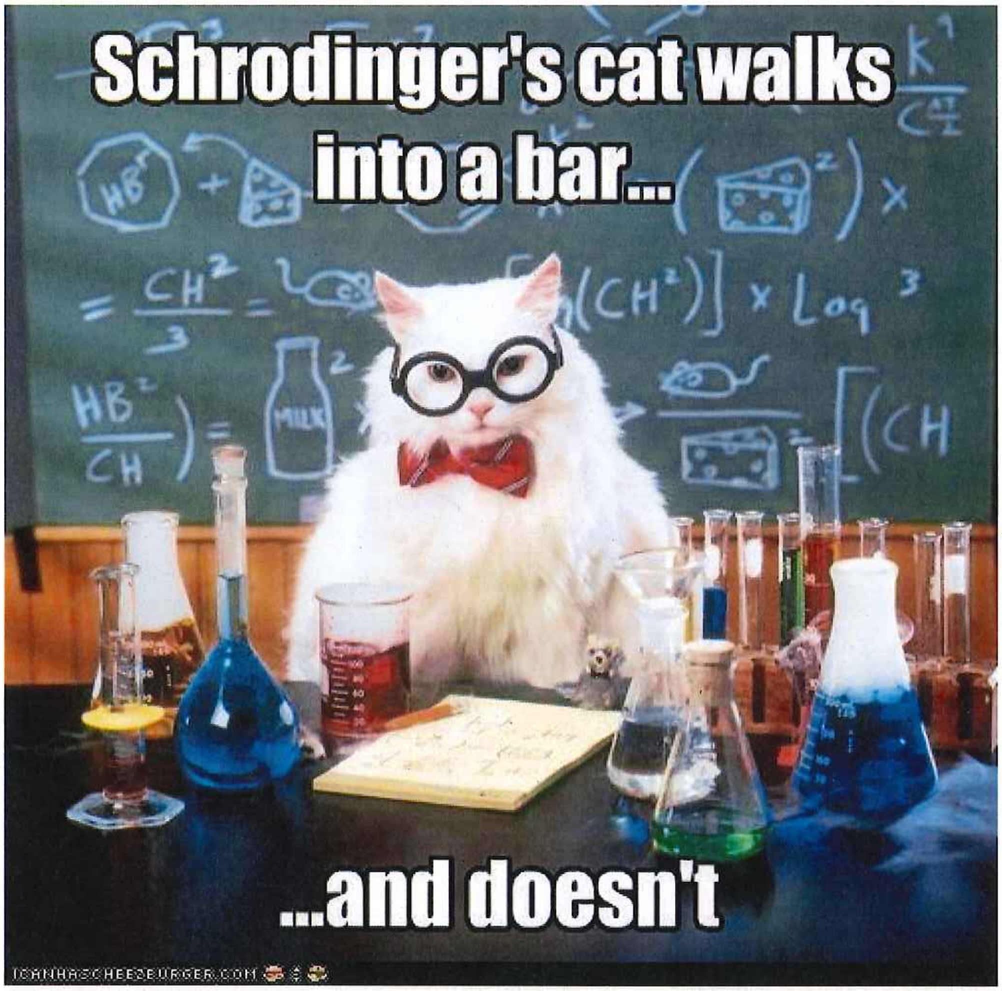
When analized using a balanced photodetector

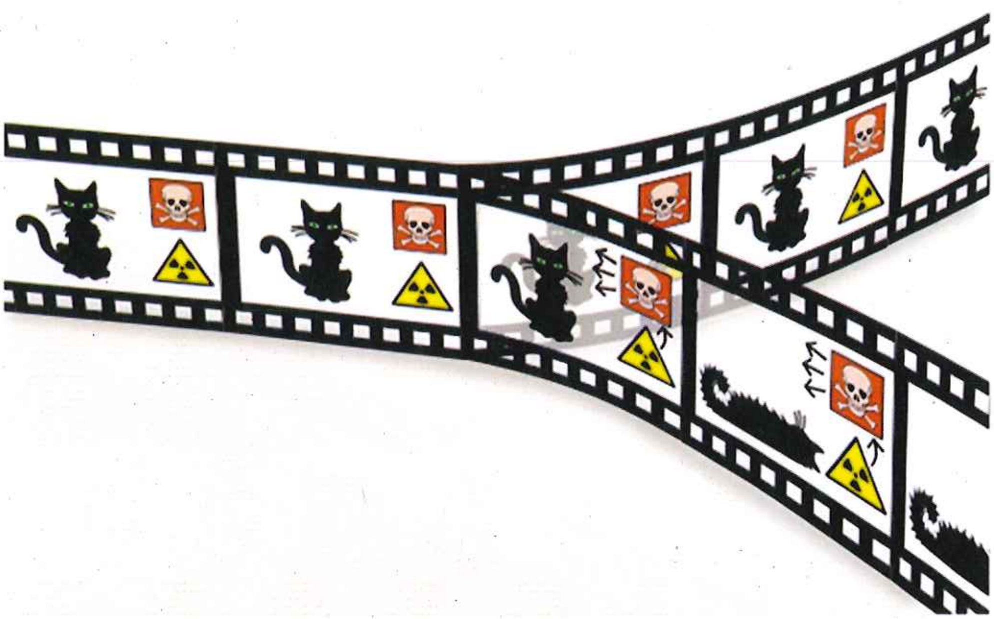
$$\Delta(\Delta n) = 4|\alpha_{LO}|^2 \langle \Delta \hat{X}_\theta^2 \rangle$$

min: $|\alpha_{LO}|^2 e^{-2r}$

max: $|\alpha_{LO}|^2 e^{2r}$







$|\alpha\rangle$

$|-\alpha\rangle$

Schrodinger cat state

$$|\psi\rangle = \mathcal{N}\left(|\alpha\rangle + e^{-i\theta}|-\alpha\rangle\right)$$

$$\langle\beta|\alpha\rangle = e^{-\frac{1}{2}|\alpha|^2 - \frac{1}{2}|\beta|^2 + \beta^*\alpha}$$

$$\langle\alpha|-\alpha\rangle = e^{-2|\alpha|^2} \ll 1 \quad \text{for large } \alpha$$

So the "Shrodinger cat" state consists of two "almost orthogonal" distinguishable "almost classical" states.

$$1 = \mathcal{N}^2\left(\langle\alpha| + e^{i\theta}\langle-\alpha|\right)\left(|\alpha\rangle + e^{-i\theta}|-\alpha\rangle\right) =$$
$$= \mathcal{N}^2\left(\langle\alpha|\alpha\rangle + \langle-\alpha|-\alpha\rangle + 2\,\mathrm{Re}\left(e^{i\theta}\langle-\alpha|\alpha\rangle\right)\right) =$$
$$= \mathcal{N}^2\left(2 + 2e^{-2|\alpha|^2}\cos\theta\right)$$

$$\mathcal{N} = \frac{1}{\sqrt{2 + 2e^{-2|\alpha|^2}\cos\theta}}$$

Three important cat states

Even cat: $\theta = 0$ $\quad |\psi_e\rangle = \frac{1}{N_e}\left(|\alpha\rangle + |-\alpha\rangle\right)$

Odd cat: $\theta = \pi$ $\quad |\psi_o\rangle = \frac{1}{N_o}\left(|\alpha\rangle - |-\alpha\rangle\right)$

Yurke-Stoler cat: $\theta = \frac{\pi}{2}$ $\quad |\psi_{YS}\rangle = \frac{1}{\sqrt{2}}\left(|\alpha\rangle + i|-\alpha\rangle\right)$

Such states are extremely hard to create and observe, since they are extremely prone to decoherence and tend to collapse into a mixed state

$$\hat{\rho} = \frac{1}{2}\left(|\alpha\rangle\langle\alpha| + |-\alpha\rangle\langle-\alpha|\right)$$

How to distinguish these for states

Photon statistics

$$|\alpha\rangle = e^{-\alpha^2/2} \sum \frac{\alpha^n}{\sqrt{n!}} |n\rangle \qquad |-\alpha\rangle = e^{-\alpha^2/2} \sum \frac{(-\alpha)^n}{\sqrt{n!}} |n\rangle$$

Even state $|\alpha\rangle + |-\alpha\rangle = e^{-\alpha^2/2} \sum_{m=0}^{\infty} \frac{2\alpha^{2m}}{\sqrt{(2m)!}} |2m\rangle$ only even-photon states

$$N_e = \frac{1}{\sqrt{2+2e^{-2\alpha^2}}}$$

$$P_{2m}^{(even)} = \frac{1}{2+2e^{-2\alpha^2}} e^{-\alpha^2} \frac{4\alpha^{4m}}{(2m)!} = \frac{2e^{-\alpha^2}}{1+e^{-2\alpha^2}} \frac{\alpha^{4m}}{(2m)!}$$

Odd state $|\alpha\rangle - |-\alpha\rangle = e^{-\alpha^2/2} \sum_{m=0}^{\infty} \frac{2\alpha^{2m+1}}{\sqrt{(2m+1)!}} |2m+1\rangle$

$$P_{2m+1}^{(odd)} = \frac{2e^{-\alpha^2}}{1-e^{-2\alpha^2}} \frac{\alpha^{2(2m+1)}}{(2m+1)!}$$ only odd-photon state

However, Yurke-Stoler states, regular coherent states and statistical mixture have identical photon distribution!

What about quadrature measurements

Even state

$$\langle(\Delta X_1)^2\rangle = \frac{1}{4} + \frac{\alpha^2}{1+e^{-2\alpha^2}}$$

$$\langle(\Delta X_2)^2\rangle = \frac{1}{4} - \frac{\alpha^2 e^{-2\alpha^2}}{1+e^{-2\alpha^2}}$$ ← non-classical

Odd state

$$\langle(\Delta X_1)^2\rangle = \frac{1}{4} + \frac{\alpha^2}{1-e^{-2\alpha^2}}$$

$$\langle(\Delta X_2)^2\rangle = \frac{1}{4} + \frac{\alpha^2 e^{-2\alpha^2}}{1-e^{-2\alpha^2}}$$

Yurke-Stoler state

$\langle(\Delta X_1)^2\rangle = \frac{1}{4} + \alpha^2$

$\langle(\Delta X_2)^2\rangle = \frac{1}{4} - \alpha^2 e^{-4\alpha^2}$ ← non-classical
but $\alpha^2 e^{-4\alpha^2} \ll 1$

Mixed state

$\langle(\Delta X_1)^2\rangle = \frac{1}{4} + \alpha^2$
$\langle(\Delta X_2)^2\rangle = 1/4$