Olomouc Seminar

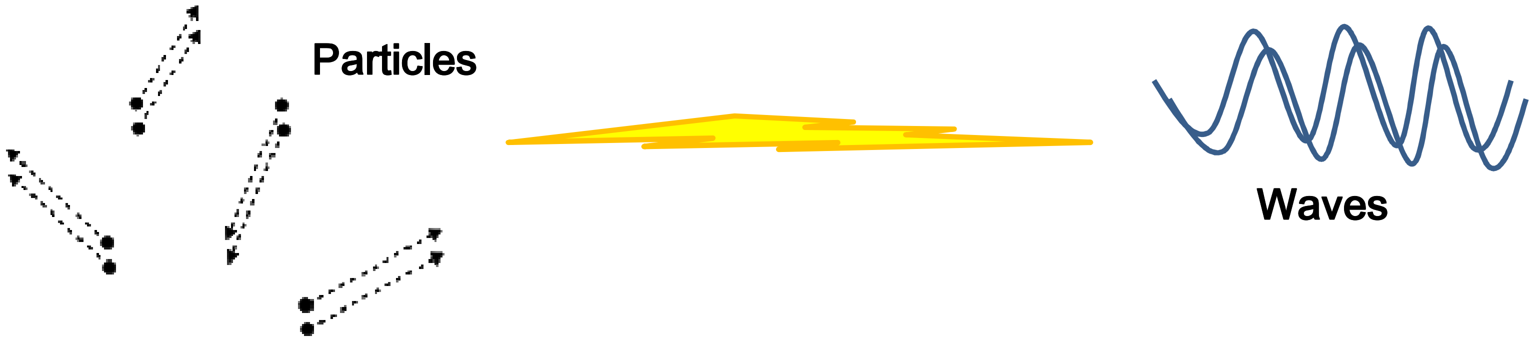
Decoherence effects on quantum teleportation:

transfer of information encoded into particles and fields

Kimin Park

Nov 5th, 2012

european social fund in the czech republic
EUROPEAN UNION
MINISTRY OF EDUCATION, YOUTH AND SPORTS
OP Education for Competitiveness
INVESTMENTS IN EDUCATION DEVELOPMENT
CMQC Center for Macroscepic Quantum Control @ SNU



- Information transfer conveyed by particle and fields
- Environmental and device effect

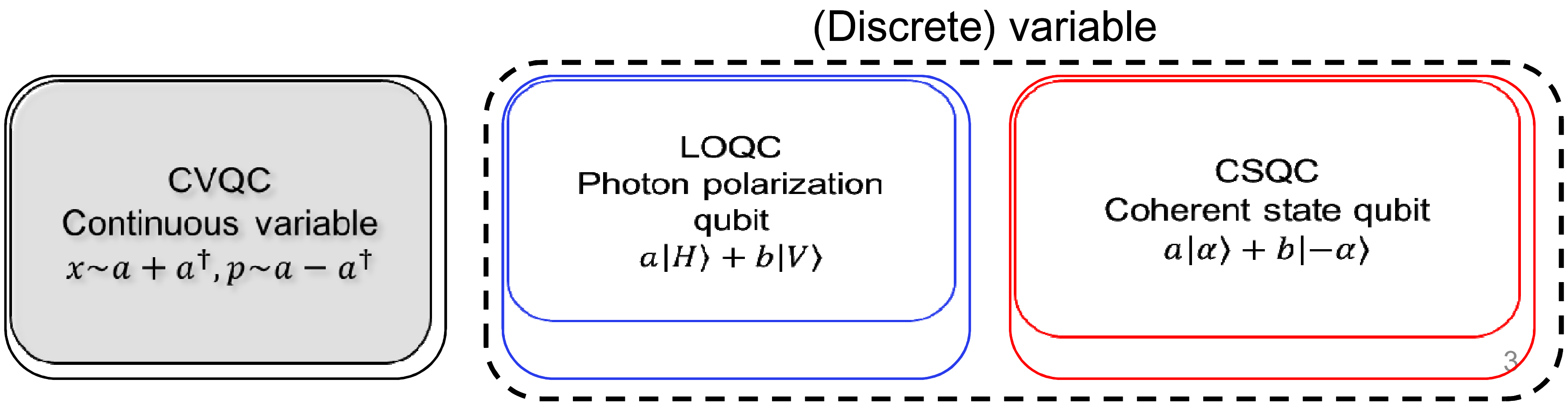
Particles and fields

- Wave-particle duality: Bohr's Complementarity principle
- Wave-particle superposition (Tang et al.), Wave-particle conversion (Miwa et al.)

- *Particle-like* qubit: Photons $|H\rangle$,$|V\rangle$,
- *Field-like* qubit: coherent states $|\alpha\rangle$, $|-\alpha\rangle$ (Cochrane et al., Jeong and Kim, Ralph et al.),

Single-rail qubit $|1\rangle$, $|0\rangle$ (Lund and Ralph)

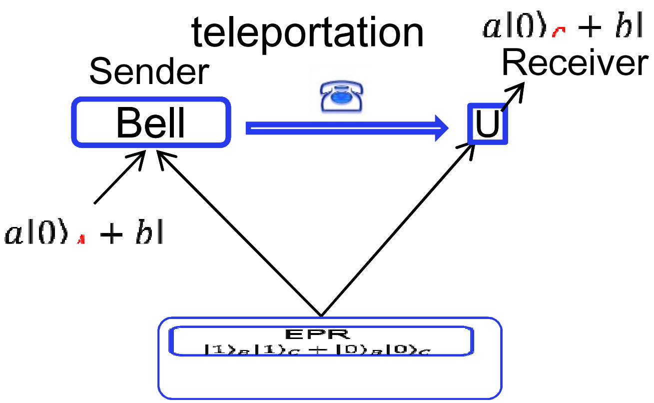
Optical QIP



Information transfer (Communication)

	Classical Means	Quantum Means
Classical Information	**Classical communication**	• **Superdense coding** • **Quantum Key Distribution (e.g. BB84, E91)**
Quantum Information	• **Measure and prepare** • **Direct sending**	• **Teleportation (Bennett et al.)** • **Remote state preparation (Bennett et al.)** • **Interaction-mediated state transfer (e.g. Spin chain quantum wire)**

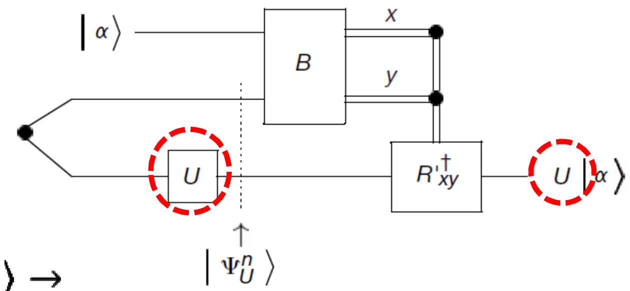
Quantum teleportation



- Difficult photon-photon coupling

$|\psi\rangle \rightarrow U|\psi\rangle \overset{G}{\Rightarrow} |\alpha\rangle \rightarrow$

- Off-line preparation & operation



Gate teleportation (Gottesman *et al.*, Nature **402**, 390 (1999))

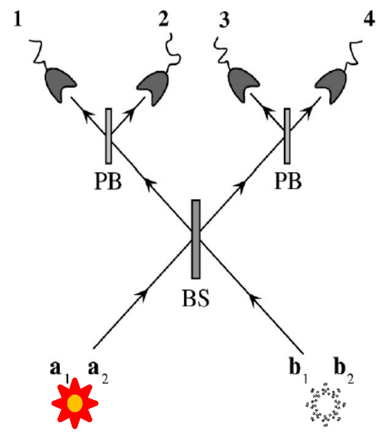
Bell measurement

Photon polarization Bell states

$$|B_{1,2}\rangle = \frac{1}{\sqrt{2}}(|H\rangle|H\rangle \pm |V\rangle|V\rangle)$$

$$|B_{3,4}\rangle = \frac{1}{\sqrt{2}}(|H\rangle|V\rangle \pm |V\rangle|H\rangle)$$

- When one or both photons are removed, "failure".
- Success probability limited by **1/2**.



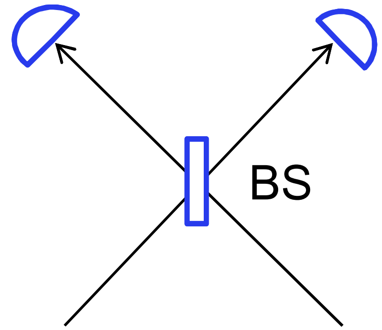
(Lütkenhaus et al., PRA 59, 3295 (1999))

Coherent state Bell states

$$|B_{1,2}\rangle = N_{1,2}\ (|\alpha\rangle|\alpha\rangle \pm |-\alpha\rangle|-\alpha\rangle)$$

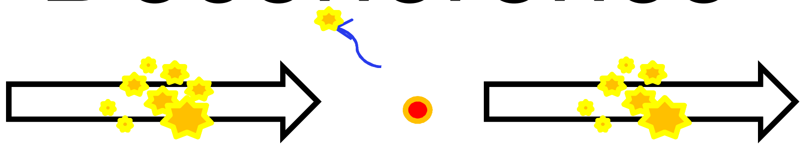
$$|B_{3,4}\rangle = N_{3,4}(|\alpha\rangle|-\alpha\rangle \pm |-\alpha\rangle|\alpha\rangle)$$

- no click: fail
- Success probability $\propto 1 - \frac{e^{-2\alpha^2}}{2}$ (99.98% for $\alpha = 2$)



(Jeong et al., PRA 64, 052308)

Decoherence



- One of the main obstacles in QIP
- Born-Markov approximation: **Dissipation** (photon-loss) by **zero temperature**, memory-less (time-local) bath
- $\frac{d\rho}{d\tau} = \boldsymbol{\gamma} \sum_i a_i \rho a_i^{\dagger} - \frac{\boldsymbol{\gamma}}{2} \sum_i (a_i^{\dagger} a_i \rho + \rho a_i^{\dagger} a_i),$
  (γ:**interaction strength**, $\boldsymbol{a}_i$: annihilation operator)
- Cause of the difference in field-like and particle-like qubits
- Probabilitic **loss of qubit**, decay of coherence.

$$|H\rangle\langle H| \longrightarrow t^2 |H\rangle\langle H| + (1-t^2)|0\rangle\langle 0|$$
$$|V\rangle\langle V| \longrightarrow t^2 |V\rangle\langle V| + (1-t^2)|0\rangle\langle 0|$$
$$|H\rangle\langle V| \longrightarrow t^2 |H\rangle\langle V| \;\; (\boldsymbol{t} = e^{-\frac{\gamma\tau}{2}})$$

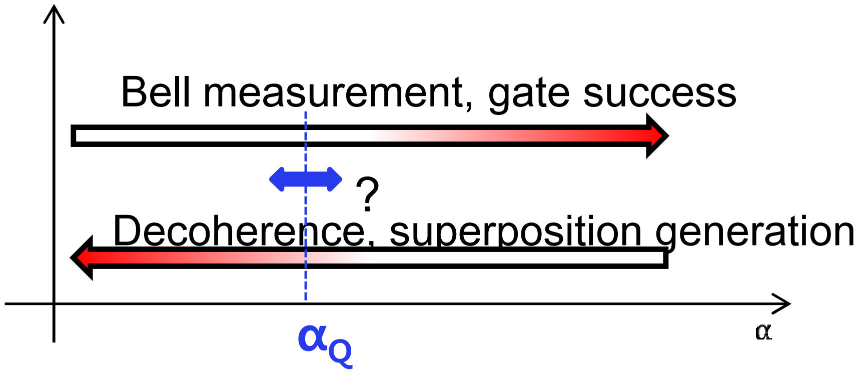
- Continuous **amplitude** decay, **exponential decay** of coherence (faster decoherence for large α).

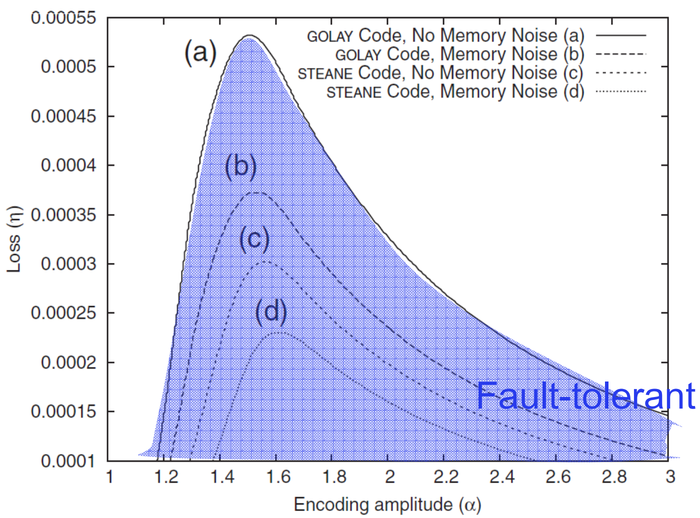
$$|\alpha\rangle\langle\alpha| \longrightarrow |t\alpha\rangle\langle t\alpha|, \; |\alpha\rangle\langle -\alpha| \longrightarrow e^{-2\alpha^2(1-t^2)} |t\alpha\rangle\langle -t\alpha|$$

Entangled Coherent States vs. Entangled Photon Pairs for Practical QIP

PHYSICAL REVIEW A **82**, 062325 (2010)

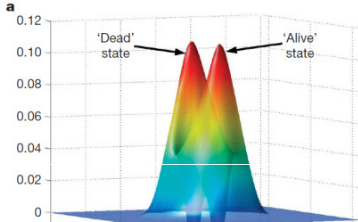
Motivation





(Lund *et al.*, PRL **100**, 030503 (2008))

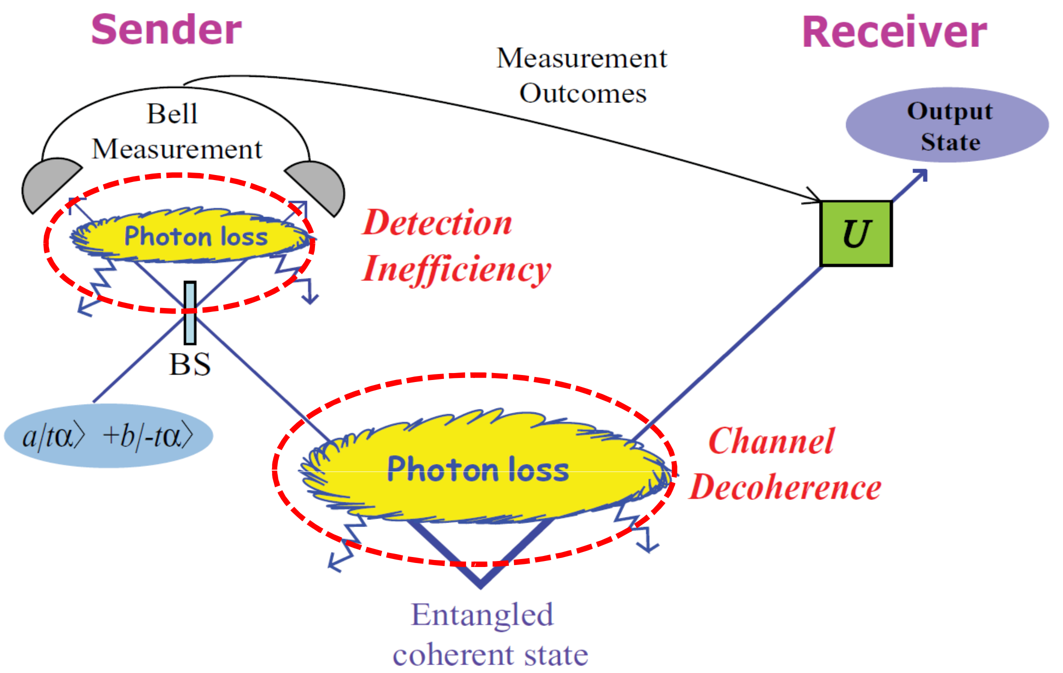
- Comparison of the *wave-like* and *field-like* information transfers
- Comparing LOQC with CSQC
- What α to use?
- Threshold error rate that allows fault-tolerance.
- $\alpha \approx 1.6$ is preferred.
- Coherent state superposition(Schrödinger's cat state)



$$|\alpha\rangle \pm |-\alpha\rangle$$

- Key resource in CSQC
- $|\alpha| = 1.76$ (Gerrits *et al.*, PRA **82**, 031802 (2010)).
- Arbitrary qubit: $|\alpha| = 1$ (Neergaard-Nielsen *et al.*, PRL **105**, 053602 (2010)).

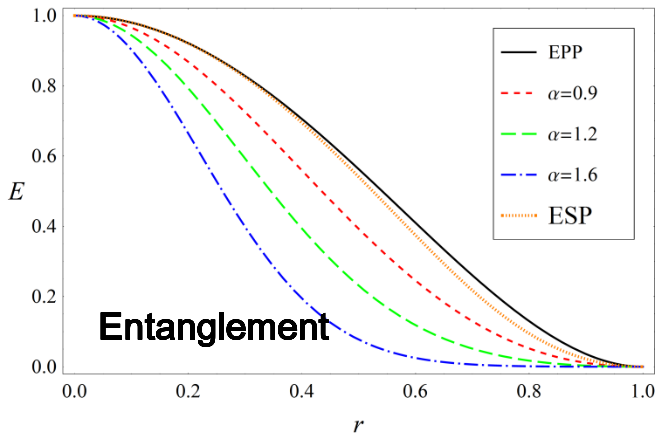
Practical Teleportation

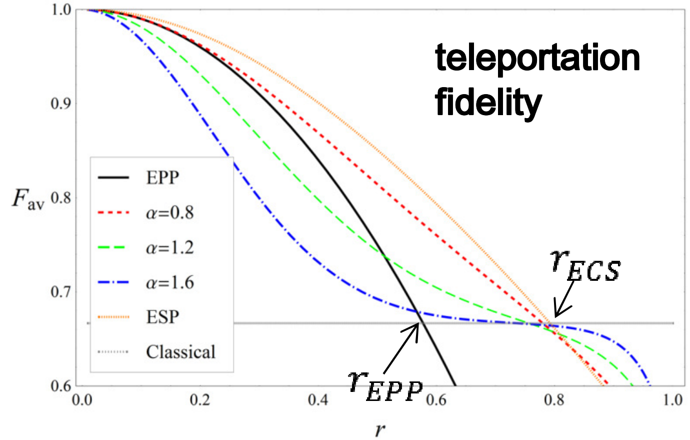


- **Teleportation under photon losses**
- Entangled Coherent state (*C*): $|\text{ECS}\rangle = N(|\alpha\rangle|-\alpha\rangle - |-\alpha\rangle|\alpha\rangle)$
- Entangled Single photon (S): $|\text{ESP}\rangle = \frac{1}{\sqrt{2}}(|1\rangle|0\rangle - |0\rangle|1\rangle)$
- Entangled Photon pair (*P*): $|\text{EPP}\rangle = \frac{1}{\sqrt{2}}(|H\rangle|V\rangle - |V\rangle|H\rangle)$

CMQC
Center for Macroscpic Quantum Control @ SNU

Entanglement vs. Teleportation fidelity





Normalized time $r = \sqrt{1 - e^{-\gamma\tau}}$

Negativity :$N = 2\sum_i |\lambda_i|$ (λ_i: negative eigenvalues of PT)

P>C

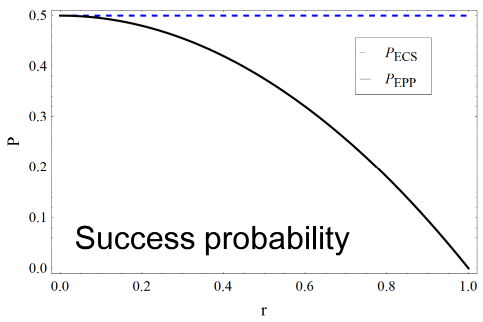
Quality of the teleportations compared.

For small $\alpha \lesssim 0.8$, *C*>*P* (main result)

C stays over **classical limit 2/3** for longer.

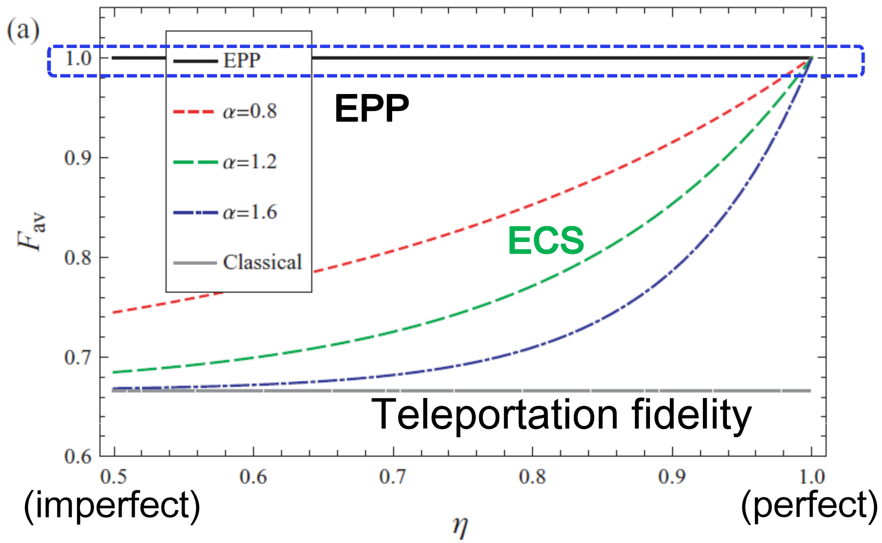
overlap ($\langle\alpha|-\alpha\rangle$) + **escape** ($|H\rangle\langle H| \to |0\rangle\langle 0|$)

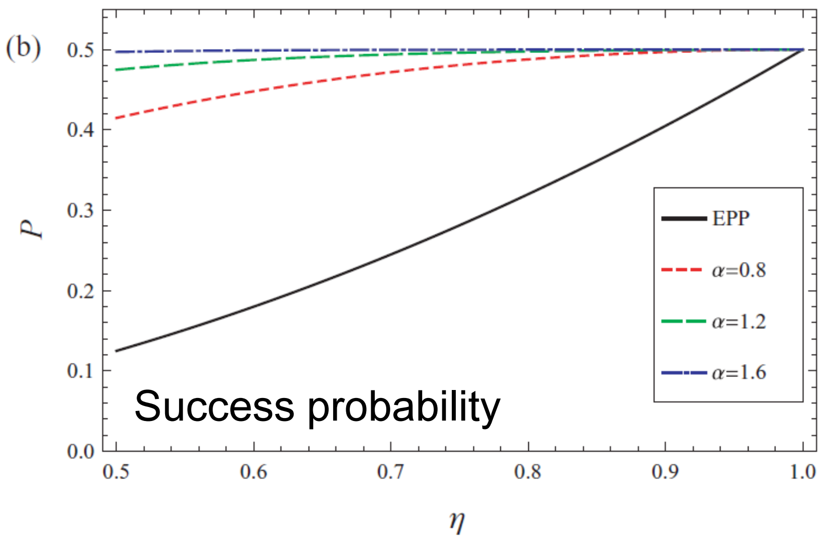
C>P for success probability for all α.



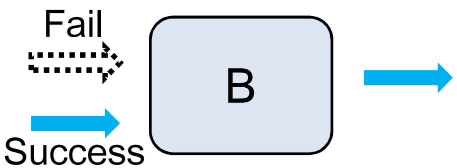
CMQC Center for Macroscpic Quantum Control @ SNU

F vs. Detection efficiency





- η: **detector efficiency** (photon loss at the detector)
- Only *C* teleportation is easily "**contaminated**" by detection efficiency.
- Polarization Bell measurement **filters out** the loss.



- Loss is less detectable for *C* Bell measurements.

CMQC
Center for Macroscopic Quantum Control @ SNU

Section summary

- Particles transfers the information faithfully, and robust to inefficient detectors, while fields does it less faithfully, but more frequently.
- Entanglement: *P*>*C*
- Teleportation: *C*>*P* ($\alpha \lesssim \mathbf{0.8}$: small amplitude),

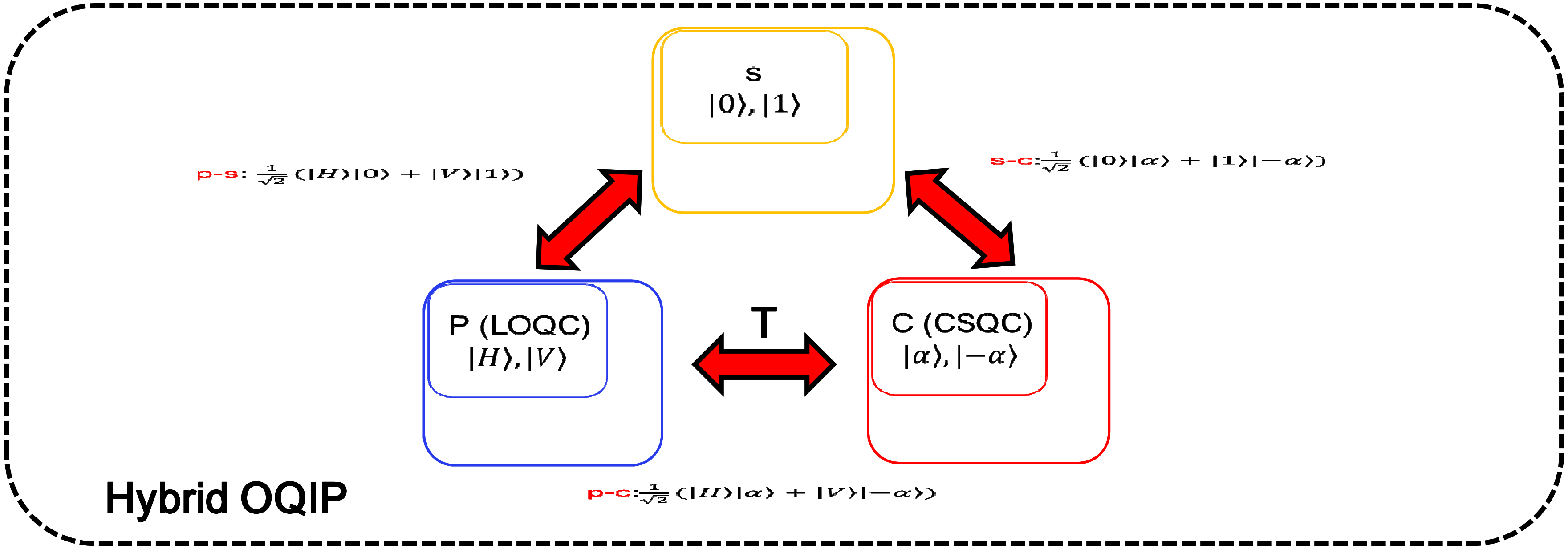
  C>*P* ($r \gtrsim \mathbf{0.577}$: strong decoherence, $\alpha \gtrsim 0.8$),

  C<*P* ($r \lesssim 0.577$, $\alpha \gtrsim 0.8$),
- Overlap of *C* and escape filtering of *P* is responsible.
- Detection inefficiency: *P*>*C*
- *P* teleportation treats **located errors** more efficiently.

Quantum Teleportation between Particle-like and Field-like Qubits under Decoherence

Submitted to PRA

Motivation

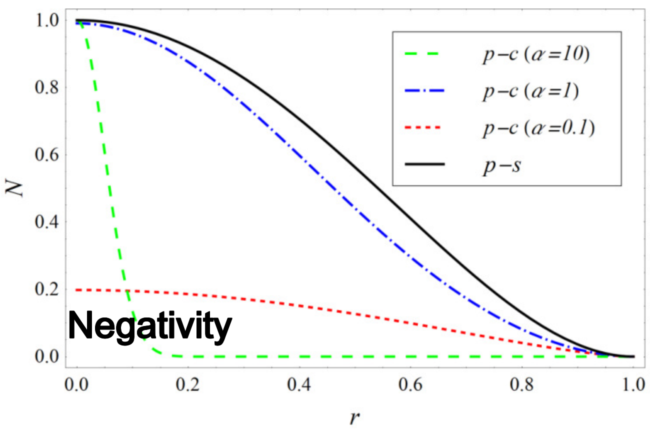


- **Difficulty** in completion of individual schemes ⇒ **Hybrid** computation
- **Teleportation** can transfer information between different systems (a quantum interface): How would information with one property transmitted to that with complementary property?
- **Different dynamics** for different qubits under the environmental effects.

Hybrid QIP

- Realization of **a gate operation combining** the qubits of different nature.
- Hybrid optical QIP using continuous-variable bus, controlled displacement atom-light interaction (van Loock et al., PRA 78, 022303 (2008))
- Polarization qubit **CNOT** gate by coherent state (Nemoto and Munro, PRL **93**, 250502 (2004))
- **Hybrid qubit** $\mathbf{a}|\boldsymbol{H}\rangle|\boldsymbol{\alpha}\rangle + \boldsymbol{b}|\boldsymbol{V}\rangle\,|-\boldsymbol{\alpha}\rangle$ (Lee and Jeong, arXiv:1112.0825 (2011)) allows a near-deterministic QIP with relatively small resources.

Negativity vs. Teleportation



p-c entanglement is largest at **α~1**

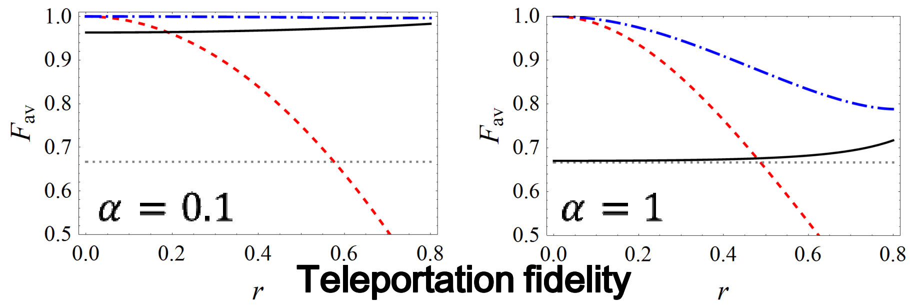
Productive for $\alpha \ll 1$:

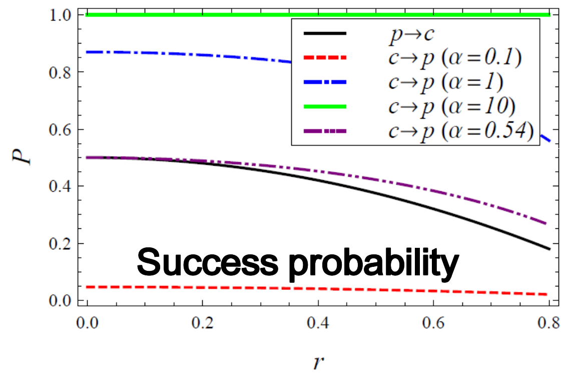
$$|H\rangle|\alpha\rangle + |V\rangle|-\alpha\rangle \sim (|H\rangle + |V\rangle)|0\rangle$$

Large dephasing for $\alpha \gg 1$:

$$|\alpha\rangle\langle-\alpha| \rightarrow e^{-2\alpha^2}|\alpha\rangle\langle-\alpha|.$$

p-s>p-c





- Smaller fidelity for large α.
- p→c > c→p (difference in fidelity)
- overlap ($\langle\alpha|-\alpha\rangle = e^{-2\alpha^2}$) + photon loss filtering.
- p→c is always larger than classical while c→p drops below it.
- c→p succeeds more frequently than p→c.

Section summary

- Hybrid optical QIP by **hybrid teleportation**.
- $p \rightarrow c,s > p \leftarrow c,s$
- For c and s, error remains in the qubit space, while not for p.
- Filtering and overlap is responsible for this.
- **Particle nature** of polarization qubit is the main cause of the difference.
- Can be interpreted as information transfer between microscopic and macroscopic objects.

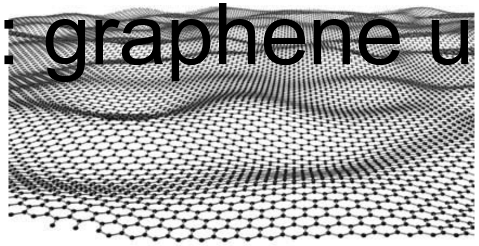
CMQC Center for Macroscpic Quantum Control @ SNU

Conclusions

- Particles transfers the information faithfully, and robust to inefficient detectors, while fields does it less faithfully, but more frequently.
- **A criteria for the choice of the amplitude** of the coherent state with regard to the decoherence effect is provided.
- **A hybrid strategy of optical QIP schemes** having different advantages and disadvantages is investigated under realistic situations.

Future works

- Light-matter interfaced QIP (Yao and Belyanin, Phys. Rev. Lett. 108, 255503 (2012).): graphene under magnetic field



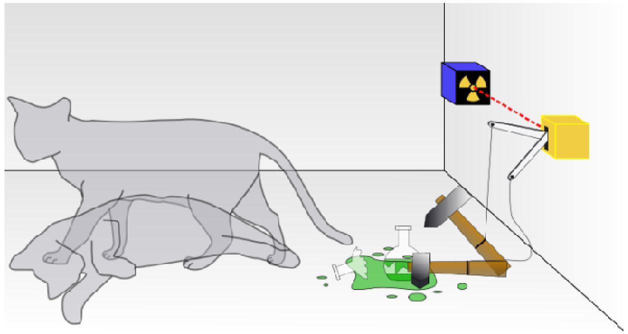
- Decoherence and Macro-realism (Kofler and Brukner, Phys. Rev. Lett. 99, 180403 (2007).)

- Interacting quantum-classical systems (Elze, Phys. Rev. A 85, 052109 (2012).)

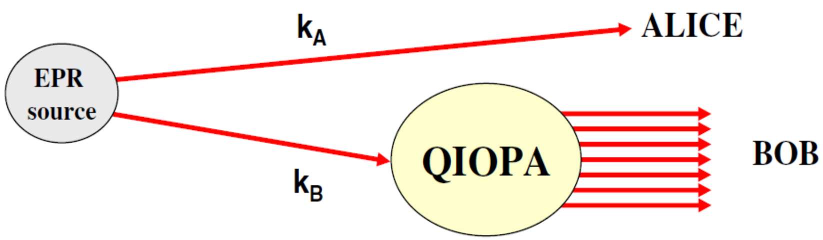
- Thank you!

Center for Macroscpic Quantum Control @ SNU

micro-Macro entanglement



Schrödinger's cat.

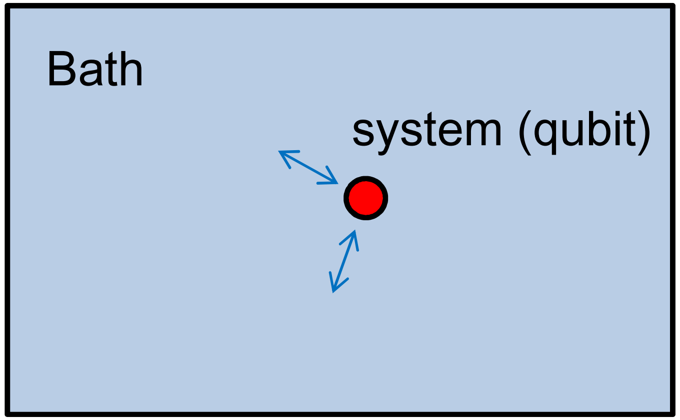


de Martini *et al.,* PRL **100**, 253601 (2008).

- $\frac{1}{\sqrt{2}}(|H\rangle|\alpha\rangle + |V\rangle|-\alpha\rangle)$ may be interpreted as an **micro-macro entanglement.**

- $|\Sigma\rangle = \frac{1}{\sqrt{2}}(|H\rangle|\Phi^+\rangle + |V\rangle|\Phi^-\rangle)$ is generated via quantum-injected **optical parametric amplification** (QI-OPA).

Decoherence

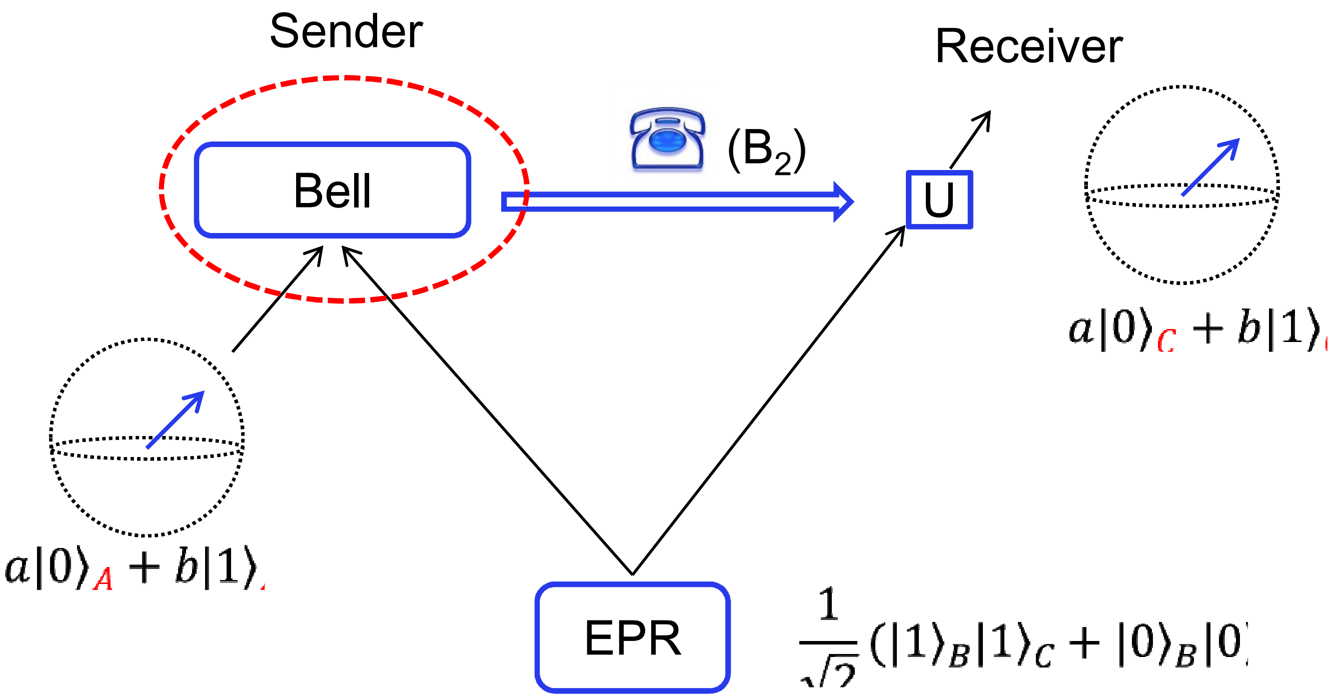


- $(a|0\rangle + b|1\rangle)_S|0\rangle_E \Rightarrow a|0\rangle|0\rangle + b|1\rangle|1\rangle$
- When only the system is observed, the reduced density matrix is seen as a mixture.

$$\rho = \begin{pmatrix} |a|^2 & 0 \\ 0 & |b|^2 \end{pmatrix}$$

Quantum teleportation

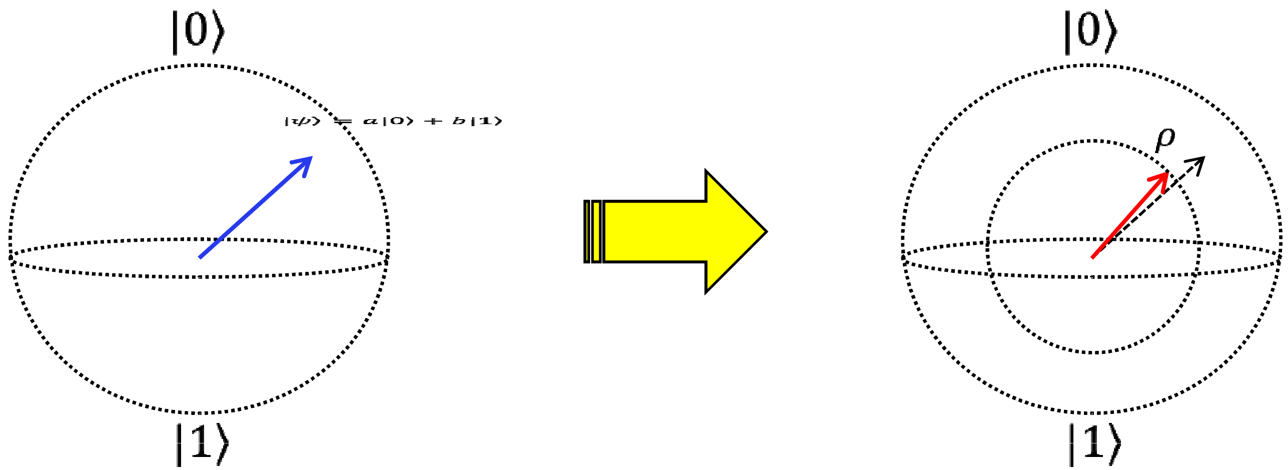
(Bennett *et al.*, PRL 70,1895 (1993))



- Central element of QIP
- Information is conveyed to another mode nonlocally.
- $\sim \boldsymbol{I}$
- Need a Bell measurement and entangled state.

CMQC
Center for Macroscopic Quantum Control @ SNU

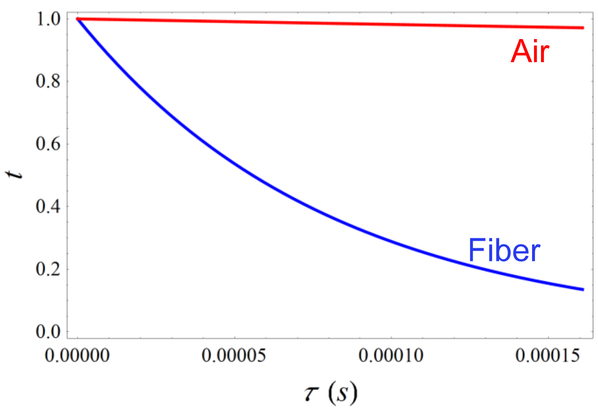
Teleportation fidelity



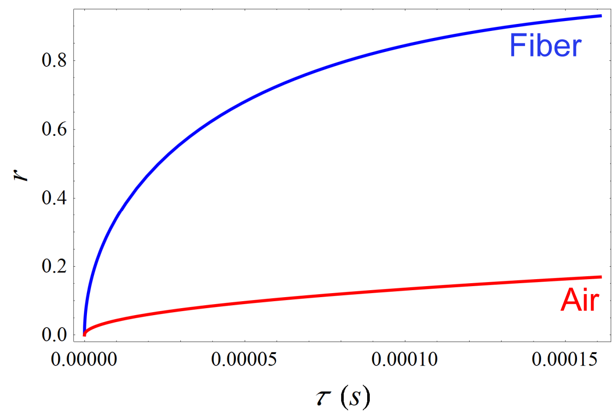
- Pure input state $|\psi\rangle$ → Mixed output state ρ
- $F = \int \mathrm{d}\psi \, \langle\psi|\rho|\psi\rangle$
- Classical limit (no-cloning bound): 2/3

Attenuation

- Optical fiber: $\gamma_F \approx 1.2 \times 10^4 s^{-1}$, 0.18 dB/km (van Loock *et al.*, PRA 78, 062319 (2008))
- Air(rayleigh scattering): $\gamma_a \approx 1.8 \times 10^2 s^{-1}$ (Sneep and Ubachs, JQSRT 92, 293 (2005)).



Coherent amplitude damping



Time rescaling

CMQC
Center for Macroscpic Quantum Control @ SNU

Summary of last talk (reminder)

- Quantum aspect of information can bring **a significant improvement** in security and computation power.

- There exists **two (discrete) optical QIP schemes** using photon polarization and coherent states, which possess different advantages and disadvantages.

- **Teleportation** is an important element for both.

CMQC
Center for Macroscpic Quantum Control @ SNU

Reminder

- Decoherence is caused by **the interaction of an system** with its environment, and is an phenomenon a system generally loses its quantum properties.

- **Dissipation** (photon loss) is the dominant decoherence mechanism for **optical** systems.

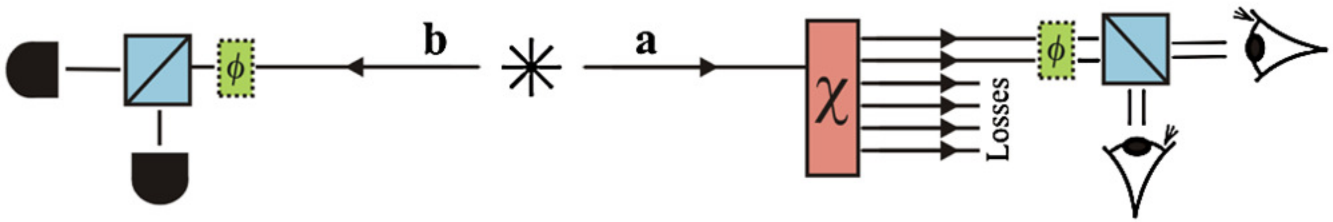
- A photon polarization qubit suffers an escape effect, while a coherent state qubit suffers a decay of its amplitude and dephasing.

Progress made since

- I wrote my thesis.
- Summarized a more tight backgrounds about hybrid QIPs.
- Made the analysis more clear.

micro-Macro entanglement

- Sekatski *et al.*, Phys. Rev. Lett. **103**, 113601 (2009).
- $|\Sigma\rangle = \frac{1}{\sqrt{2}}(|H\rangle|\Phi^+\rangle + |V\rangle|\Phi^-\rangle)$ observed with human eyes shows a Bell-violation.



Teleportation fidelity and singlet fraction

(Horodecki *et al.*, PRA **60**, 1888 (1999))

- Average fidelity of quantum teleportation $f = \int \langle\psi|\Lambda(|\psi\rangle\langle\psi|)|\psi\rangle$ is related to maximal entangled fidelity of the channel $F(\rho^{\Lambda}) = \mathrm{Tr}(|\Phi\rangle\langle\Phi|\rho^{\Lambda})$.
- $f = \frac{dF(\rho^{\Lambda})+1}{d+1}$, for which ρ^{Λ} should have a local reduced density matrix proportional to identity operator.

Entanglement and teleportation

- A mixed state which does not violate Bell inequality may be useful for teleportation: $\rho = \frac{1}{8} I + \frac{1}{2} |\psi\rangle\langle\psi|$ (Popescu, PRL **72**, 797 (1994)).

- A set of states that shows Bell nonlocality is a strict subset of non-separable states (Werner, PRA **40**, 4277 (1989)).

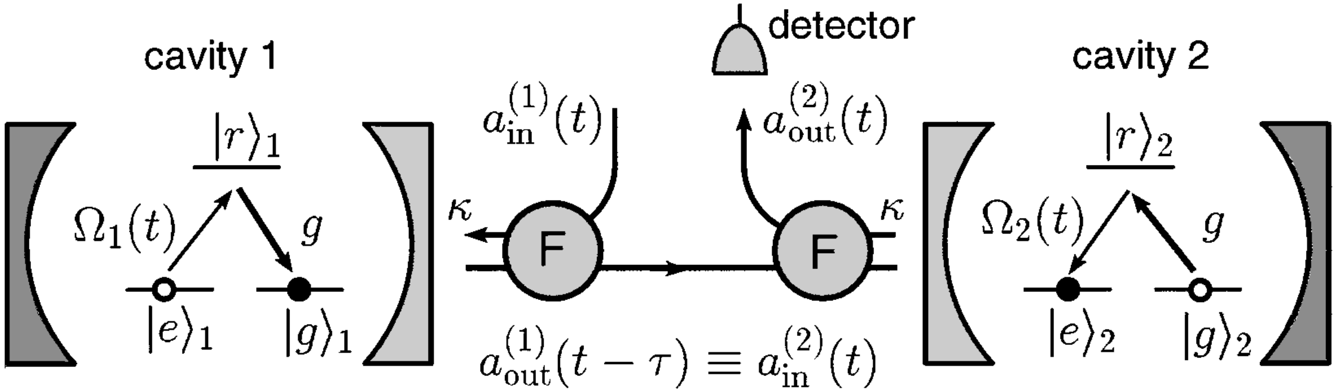
CMQC
Center for Macroscpic Quantum Control @ SNU

Contributions to the Field

- Suggested a new criteria for a choice of amplitude of coherent state qubit.

- Investigated the crucial element of a new strategy of hybrid QIP.

Hybrid QIP

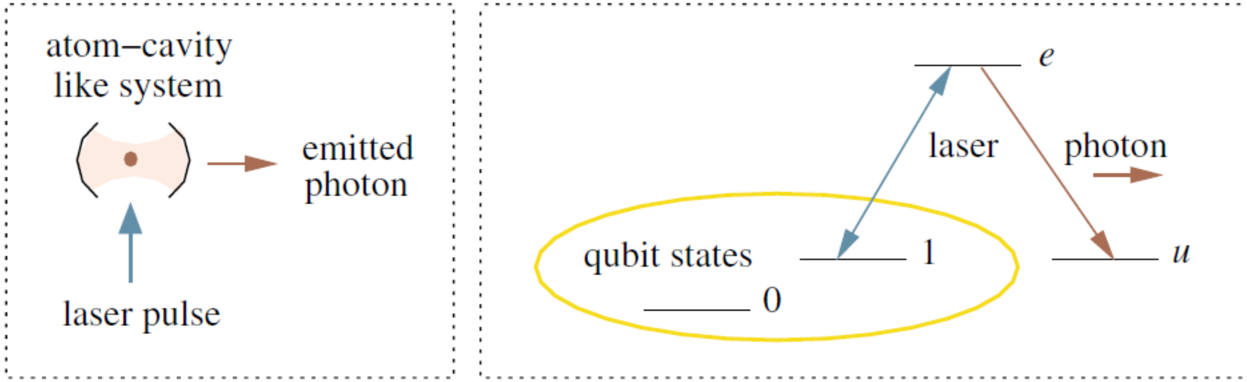


- Mostly centered on the realization of a gate operation utilizing the qubits of different nature.

- Cirac *et al.*, Phys. Rev. Lett **78**, 3221 (1997).
- $(c_g|g\rangle + c_e|e\rangle)|g\rangle \dashrightarrow |g\rangle(c_g|g\rangle + c_e|e\rangle)$

CMQC
Center for Macroscpic Quantum Control @ SNU

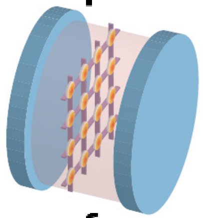
Hybrid QIP



- Lim *et al.*, Phys. Rev. Lett. **95**, 030505 (2005)
- Atom-cavity-like system (sources for the generation of single photons on demand)
- Two-qubit phase gate: $U_{CZ} = \mathrm{diag}(1,1,1,-1)$

Hybrid QIP

- Reliable reading and writing of **topologically protected quantum memory** using an **atomic or photonic qubit** (Jiang *et al.,* Nature Physics **4**, 482 (2008)).

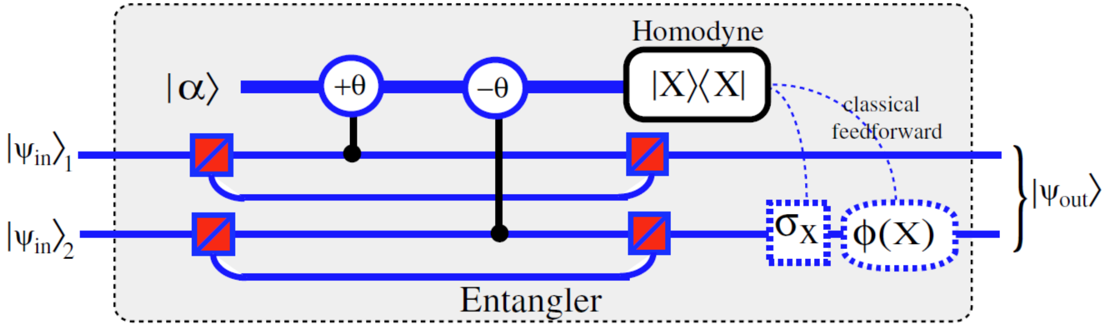


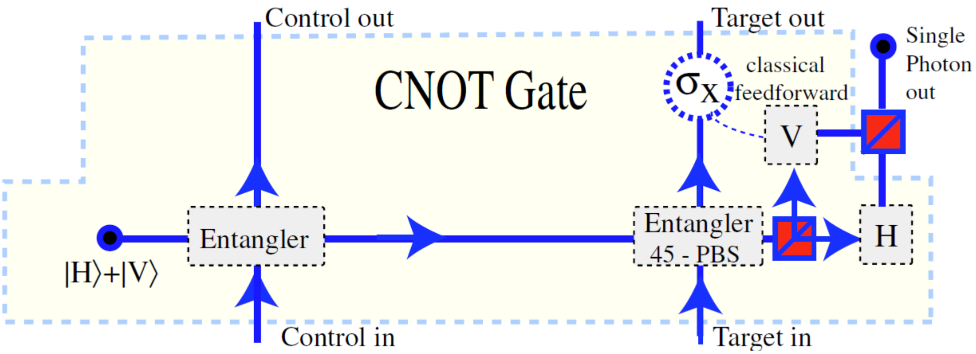
- Hybrid quantum computer of **continuous** and **discrete** quantum variables (Lloyd, arXiv: quant-ph/0008057 (2000)), utilizing the easiness of quantum Fourier transform in continuous variable QIP.

- **Hybrid qubit** in the form of $|0_L\rangle = (|H\rangle + |V\rangle)|\alpha\rangle$, $|1_L\rangle = (|H\rangle - |V\rangle)|\alpha\rangle$ may show advantages in universal gate operation and fault tolerance (Lee and Jeong, arXiv:1112.0825 (2011)).

CMQC Center for Macroscepic Quantum Control @ SNU

Hybrid QIP

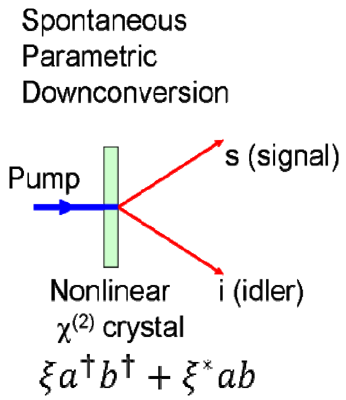


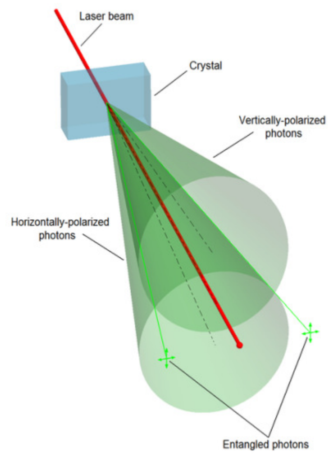


- Nemoto *et al.*, Phys. Rev. Lett. **93**, 250502 (2004).
- Near-deterministic **CNOT** gate using a part containing a coherent state.
- A weak cross-Kerr nonlinearity ($U = \exp[i\theta n_a n_p]$) with strong coherent state and

Entanglement generation

- ECS: $(|\alpha\rangle + |-\alpha\rangle)|0\rangle \overset{\text{BS}}{\Longrightarrow} \left|\frac{\alpha}{\sqrt{2}}\right\rangle\left|-\frac{\alpha}{\sqrt{2}}\right\rangle + \left|\frac{\alpha}{\sqrt{2}}\right\rangle\left|-\frac{\alpha}{\sqrt{2}}\right\rangle$
- EPP:





(Kwiat *et al.*, PRL **75**, 4337 (1995))

Entanglement generation

- p-c: $(|H\rangle + |V\rangle)|\alpha\rangle \overset{NL}{\Rightarrow} |H\rangle|\alpha\rangle + |V\rangle|\alpha e^{-i\phi}\rangle$ (Gerry, PRA **59**, 4095 (1999))

Polarization qubit and single-rail qubit

- Photon polarization (**dual-rail** for spatial-mode)
- $|H\rangle = |1\rangle|0\rangle$, $|V\rangle = |0\rangle|1\rangle$ $(|1\rangle = \hat{a}^\dagger|0\rangle)$
- qubit: $a|H\rangle + b|V\rangle$

- **Single-rail** photon qubit
- qubit: $a|0\rangle + b|1\rangle$
- Called a **Field-like** encoding together with coherent state qubit

Research Interests

- **Decoherence**: quantum → classical
- **Hybrid QIP**
- Measurement: weak measurement, phase estimation

CMQC
Center for Macroscpic Quantum Control @ SNU

Backgrounds:
Quantum Information

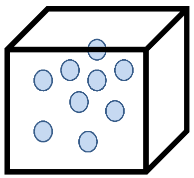
CMQC
Center for Macroscopic Quantum Control @ SNU

Quantum Information

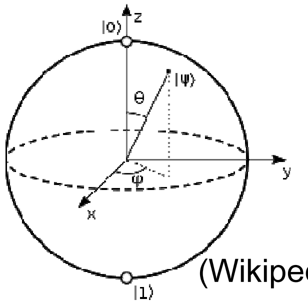
- "Information is **physical**." (Landauer 1961)

$$S(\rho) = -\mathrm{Tr}(\rho \ln \rho)$$

- "…the laws of information transmission are restricted or governed by the **laws of physics**…" (Galindo and Martin-Delgado, RMP (2002))
- "**Quantum**" aspect of information & "Informational" aspect of quantum mechanics (quantum simulator).



- qubit $\boldsymbol{a}|\mathbf{0}\rangle + \boldsymbol{b}|\mathbf{1}\rangle$ (atom, cavity, electron, quantum dot, photons…)

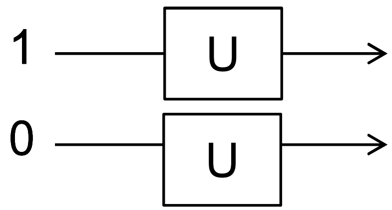


(Wikipedia)

Advantages

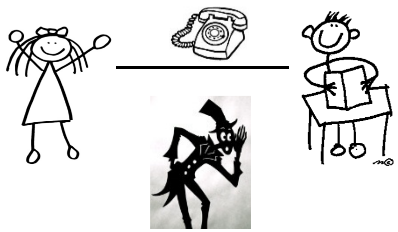
- **Exponential computation power** (quantum parallelism).

$$U(|0\rangle + |1\rangle) = U|0\rangle + U|1\rangle$$

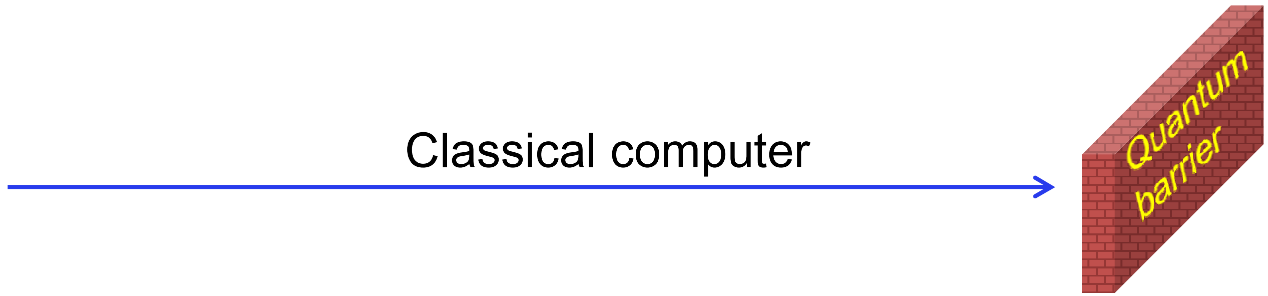


- Factoring numbers (Shor), searching the database (Grover)…
- Unconditionally **secure** (quantum key distribution)

$|\psi\rangle|0\rangle \nrightarrow |\psi\rangle|\psi\rangle$ (no-cloning)



FAQ



Q. Why should we use the “quantum” information?

A. The resources. 1 qubit ≒ ∞ bits to represent.

Q. Where is this quantum advantage from?

A. The **full space** of the state is exploited. As a price, we give up copying.