



# A Brief Introduction to Quantum Information Processing

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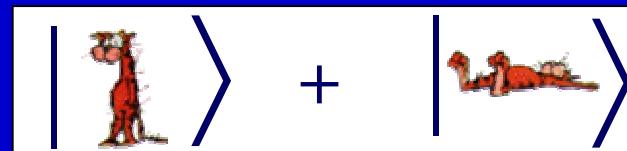
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# Quantum Superposition

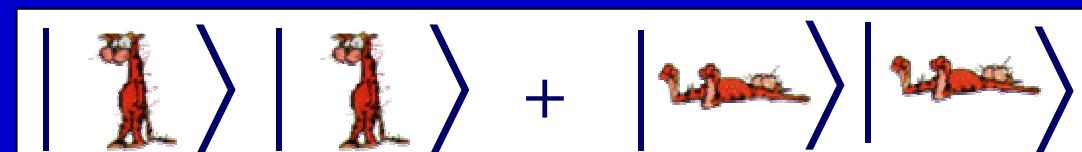
Classical Physics:  
“bit”



Quantum Physics:  
“qubit”



Quantum Entanglement:



Quantum foundations: Bell's inequality, quantum nonlocality...  
Quantum information processing: quantum communication,  
quantum computation, quantum simulation, and high precision  
measurement etc ...

## Why Quantum Information?

When information is encoded in quantum states one may outperform classical information systems in terms of

- computational capacities
- absolute security
- efficiency
- channel capacity

Because quantum information systems allow encoding information by means of  
coherent superposition of quantum states.

# Qubits: Polarization of Single Photons

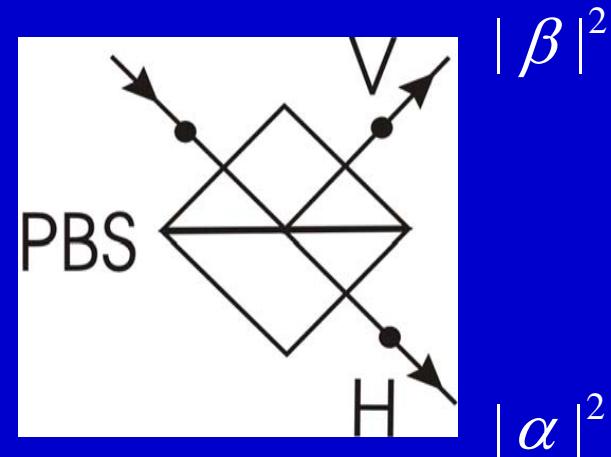
One bit of information per photon  
(encoded in polarization)

$$|H\rangle = |0\rangle$$
$$|V\rangle = |1\rangle$$

$$|\Phi\rangle = \alpha |H\rangle + \beta |V\rangle$$

Qubit:

$$|\alpha|^2 + |\beta|^2 = 1$$



Non-cloning theorem:

An unknown quantum state can not be copied precisely!

# Polarization Entangled Photon Pair 1-2

Bell states – maximally entangled states:

$$|\Phi^\pm\rangle_{12} = \frac{1}{\sqrt{2}}(|H\rangle_1|H\rangle_2 \pm |V\rangle_1|V\rangle_2)$$

$$|\Psi^\pm\rangle_{12} = \frac{1}{\sqrt{2}}(|H\rangle_1|V\rangle_2 \pm |V\rangle_1|H\rangle_2)$$

singlet:

$$|\Psi^-\rangle_{12} = \frac{1}{\sqrt{2}}(|H\rangle_1|V\rangle_2 - |V\rangle_1|H\rangle_2)$$

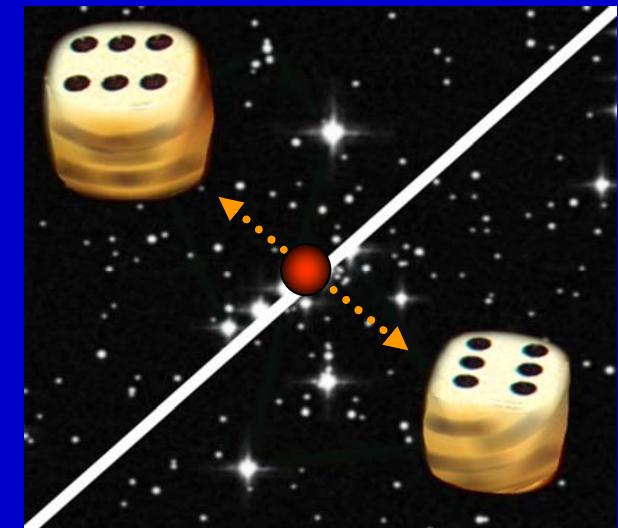
$$= \frac{1}{\sqrt{2}}(|H'\rangle_1|V'\rangle_2 - |V'\rangle_1|H'\rangle_2)$$

where

$$|H'\rangle = \frac{1}{\sqrt{2}}(|H\rangle + |V\rangle)$$

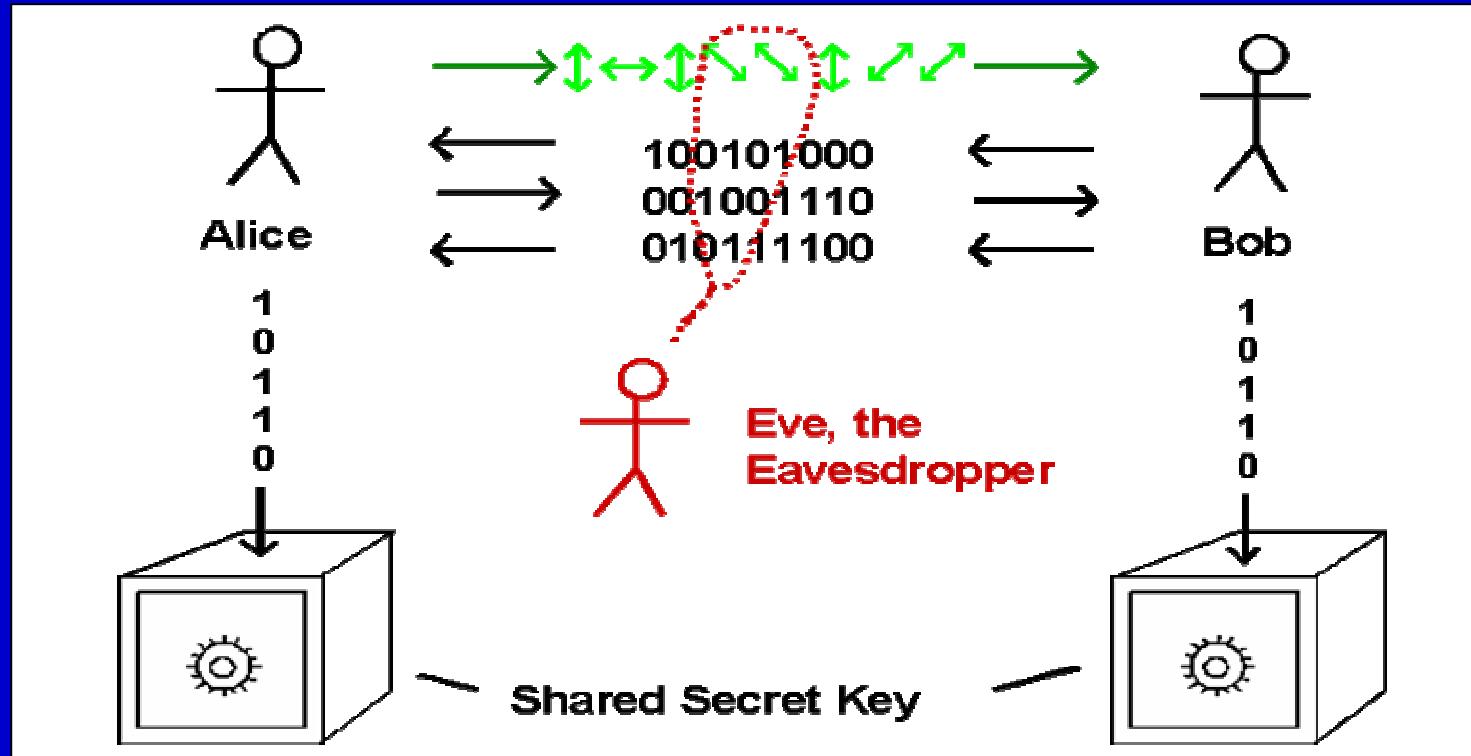
45-degree  
polarization

$$|V'\rangle = \frac{1}{\sqrt{2}}(|H\rangle - |V\rangle)$$



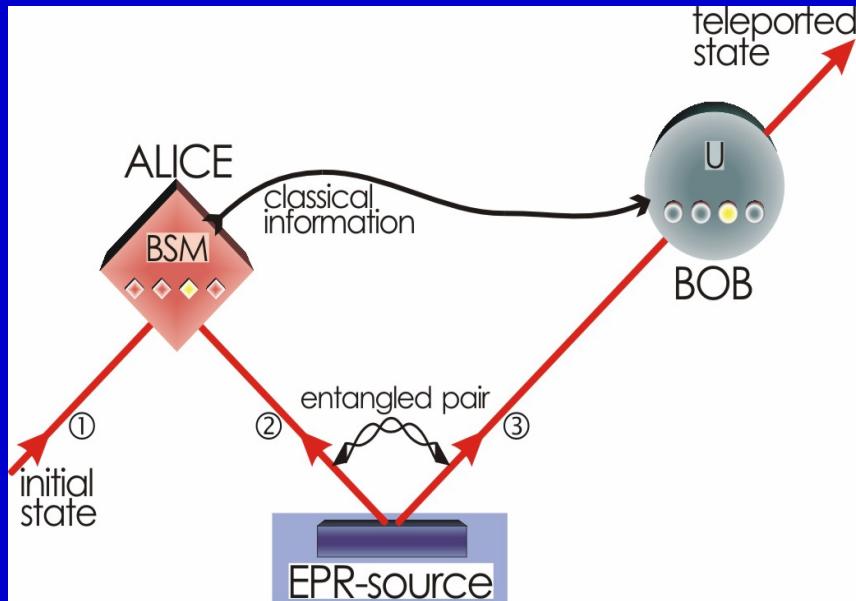
# Quantum Key Distribution (QKD)

- Single-particle-based secret key distribution:  
[C. H. Bennett & G. Brassard, BB84 protocol (1984) ]



- Entanglement-based secret key distribution:  
[A. Ekert, Phys. Rev. Lett. 67, 661 (1991) ]

# Quantum Teleportation



**Initial state**

$$|\Phi\rangle_1 = \alpha|H\rangle_1 + \beta|V\rangle_1$$

**The shared entangled pair**

$$|\Phi^+\rangle_{23} = \frac{1}{\sqrt{2}}(|H\rangle_2|H\rangle_3 + |V\rangle_2|V\rangle_3)$$

$$\begin{aligned} |\Psi\rangle_{123} &= |\Phi\rangle_1 \otimes |\Phi^+\rangle_{23} \\ &= |\Phi^+\rangle_{12} \otimes (\alpha|H\rangle_3 + \beta|V\rangle_3) + \\ &\quad |\Phi^-\rangle_{12} \otimes (\alpha|H\rangle_3 - \beta|V\rangle_3) + \\ &\quad |\Psi^+\rangle_{12} \otimes (\alpha|V\rangle_3 + \beta|H\rangle_3) + \\ &\quad |\Psi^-\rangle_{12} \otimes (\alpha|V\rangle_3 - \beta|H\rangle_3), \end{aligned}$$

**where**

$$|\Phi^\pm\rangle_{12} = \frac{1}{\sqrt{2}}(|H\rangle_1|H\rangle_2 \pm |V\rangle_1|V\rangle_2)$$

$$|\Psi^\pm\rangle_{12} = \frac{1}{\sqrt{2}}(|H\rangle_1|V\rangle_2 \pm |V\rangle_1|H\rangle_2)$$

[C. H. Bennett et al., Phys. Rev. Lett. 73, 3801 (1993)]

## Quantum Parallelism

bits	qubits
0 or 1	0 + 1
00, 01, 10 or 11	00 + 01 + 10 + 11
000, 001, 010.....	000 + 001 + 010 + .....
.	.
.	.
.	.

It allows a quantum computer to evaluate a function  $f(x)$  for many different values of  $x$  simultaneously.

$$U \sum_{i=1}^{2^N} a_i |i\rangle = \sum_i a_i U |i\rangle \quad 2^N !$$

# Quantum Computation and Simulation

**Quantum computation:**

e.g. factorizing a 400 digit integer

[P. W. Shor, in Proceeding of the 35th Annual Symposium on Foundations of Computer Science (1994).]

**Classical : 10 billion years    Quantum : 1 minute!**

Break down the RSA cryptographic system ...

**Quantum simulation:**

e.g. simulating fractional statistics of anyons

[A. Y. Kitaev, Ann. Phys. 303, 2-30 (2003)]

[Han et al., Phys. Rev. Lett. 98, 150404 (2007)]

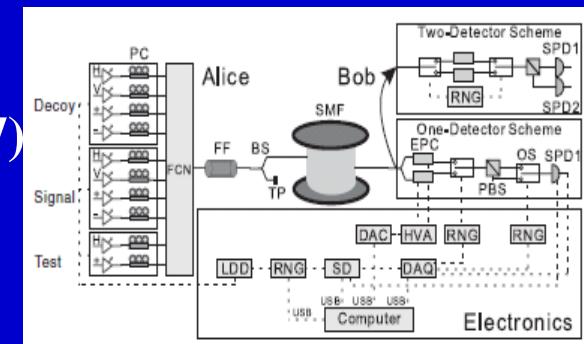
Many more...

# Quantum Key Distribution (QKD)

## Decoy-state QKD via fiber:

Hughes: Rosenberg et al., PRL 98, 010503 (2007)

Pan: Peng et al., PRL. 98, 010505 (2007)



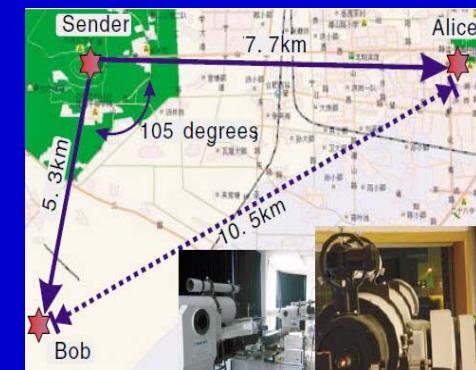
## Decoy-state QKD in free space:

Weinfurter: Schmitt-Manderbach et al., PRL 98, 010504 (2007) ~ 100km

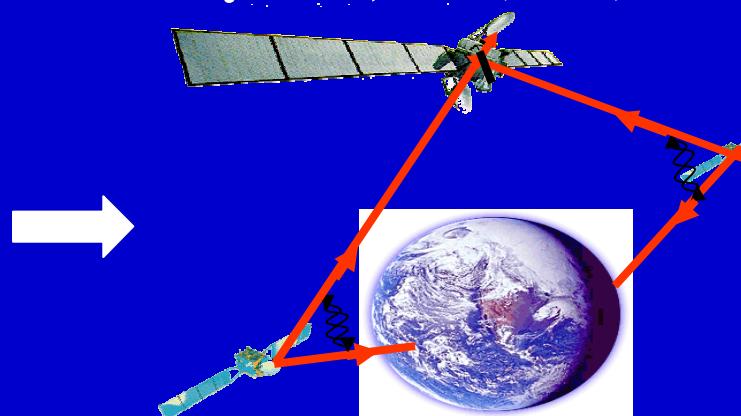
## Entanglement-based QKD in free space

Pan: Peng et al., PRL. 94, 150501 (2005)

Zeilinger: Ursin et al., Nature Physics 3, 481 (2007)



Photon loss  
Low efficiency



# Quantum Teleportation of Qubits

**Teleportation of photonic qubits:**

Bouwmeester et al., Nature 390, 575 (1997)

**Teleportation of atomic (ion) qubits:  
(with a distance 30um)**

M. Riebe et al., Nature 429, 734 (2004)

M.D. Barret et al., Nature 429, 737 (2004)

**Teleportation of photonic qubits:  
(with a distance 600m)**

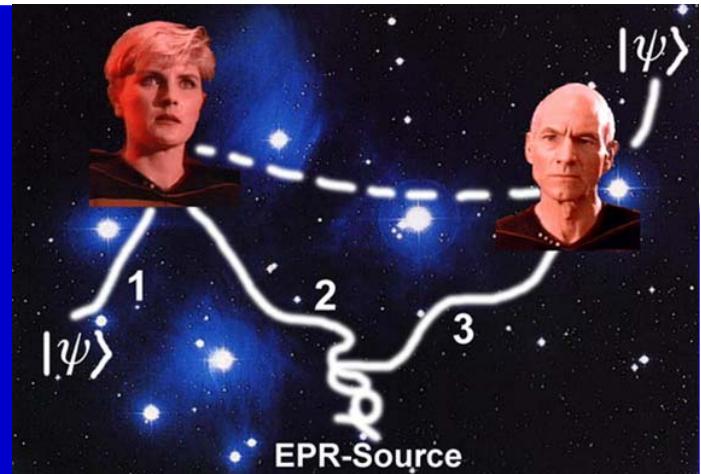
Marcikic et al., Nature 421, 509 (2003)

Ursin et al., Nature 430, 849 (2004)

**Very recently...**

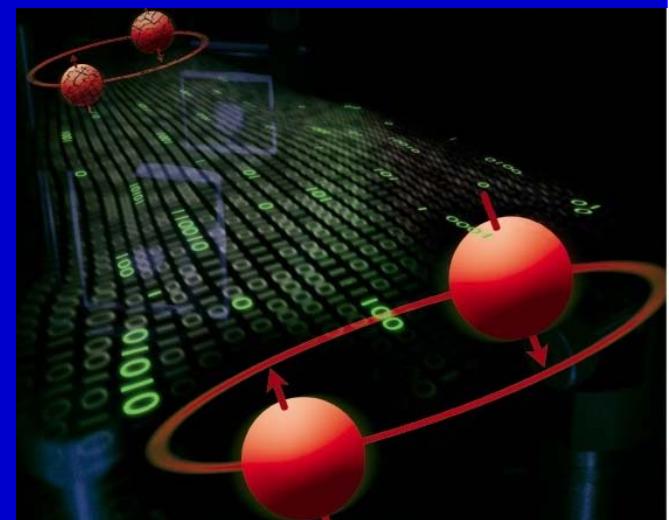
**Teleportation of a composite system**

Zhang et al., Nature Physics 2, 678 (2006)



**Photon: low efficiency**

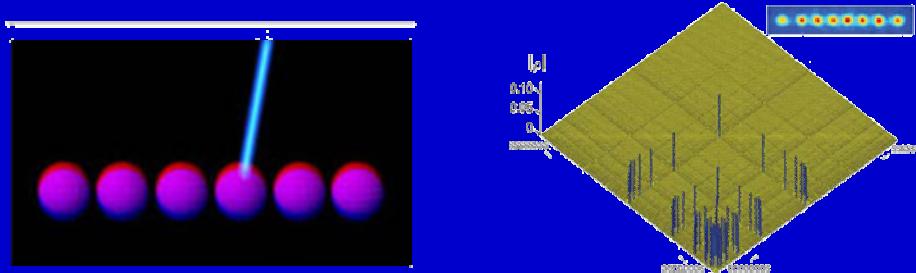
**Ion: limited distance**



# Quantum Computation with Atomic or Photonic Qubits

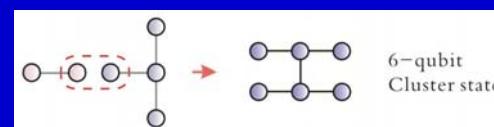
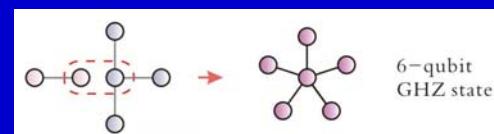
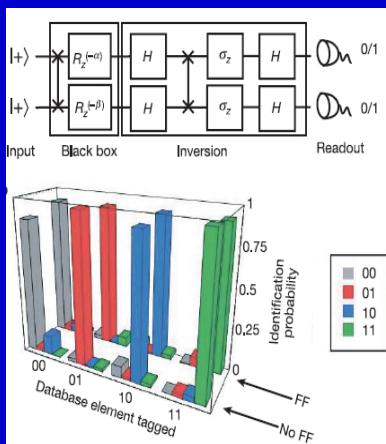
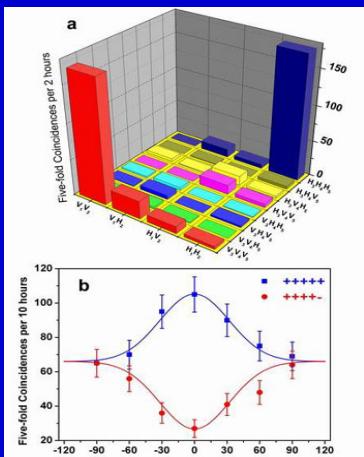
Trapped Ions:  
Suitable for the  
Circuit QC model

Decoherence!



Blatt: Leibried et al., Nature 438, 639 (2005)  
Wineland: Haffner et al., Nature 438, 643 (2005)

Photons:  
Ideal for the  
Cluster-state  
QC model



Low efficiency!

Pan: Zhao et al., Nature 430, 54 (2004)  
Zeilinger: Walther et al., Nature 434, 169 (2005)  
Pan: Lu et al., Nature Physics 3, 91 (2007)

## Outlines of the Present Lecture

- Principles of quantum physics and quantum nonlocality
- Quantum communication schemes and quantum optics realization
- Quantum computation schemes and quantum optics realization
- Quantum error-correction schemes and quantum optics realization

## Some useful textbooks and registration

Quantum Computation and Quantum Information  
written by Michael A. Nielsen and Isaac L. Chuang  
Cambridge University Press

The Physics of Quantum Information  
edited by D. Bouwmeester, A. Ekert, A. Zeilinger  
Springer-Verlag

Jian-Wei Pan

Bo Zhao

<http://quantuminformation.physi.uni-heidelberg.de/>