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Quantum Teleportation talk 5-22-2009

Quantum Teleportation

Outline

- What is Quantum Teleportation
- History of Quantum Teleportation
- Experiments with atoms: Science Magazine

What is Quantum Teleportation

- Technique to transfer quantum state of qubit(s) to recipient, so that he reproduces the same quantum state of qubit(s).

What Quantum Teleportation is Not

- No transport of energy or matter

- No communication at superluminal speed

- No copying of qubits - only moving

Reminder: Quantum Entanglement

2 particles A, B Not Entangled:

State of a system can be represented as a direct product
$|\Psi> = |\Psi>_A \otimes |\Psi>_B$

Eg, 2 possible states of each particle:
$|\Psi> = \frac{1}{\sqrt{2}}(|0>_A + |1>_A) \otimes \frac{1}{\sqrt{2}}(|0>_B + |1>_B)$

Reminder: Quantum Entanglement

2 particles A, B Entangled:
State of a system can Not be represented as a direct product
Eg:
$|\Psi> = \frac{1}{\sqrt{2}}(|0>_A \otimes |0>_B + |1>_A \otimes |1>_B)$

Reminder: Quantum Entanglement

Ways to create entangled states:

- Decay Spin-0 particle → 2 spin-1/2 particles:
$|\Psi>_{12} = \frac{1}{\sqrt{2}}(|\uparrow>_1 |\downarrow>_2 - |\downarrow>_1 |\uparrow>_2)$

- Entangled ions: electromagnetic Paul traps

- Entangled atoms: Atom-cavity experiments

- Entangled nuclear spins: NMR technique

- Photons: ”down-conversion”: nonlinear crystal: photon → pair of photons

How Quantum Teleportation Works

Heroes:
Alice and Bob

Alice has qubit
$C = |\psi >= \alpha|0 > +\beta|1 >$

Alice wants to send qubit C to Bob

How Quantum Teleportation Works

Alice and Bob share an entangled pair of qubits

$$AB = |\Phi^+ >= \frac{1}{\sqrt{2}}(|0>_A \otimes |0>_B + |1>_A \otimes |1>_B).$$

- one of Bell states

Bell states:

$$|\Phi^+ >= \frac{1}{\sqrt{2}}(|0>_A \otimes |0>_B + |1>_A \otimes |1>_B)$$

$$|\Phi^- >= \frac{1}{\sqrt{2}}(|0>_A \otimes |0>_B - |1>_A \otimes |1>_B)$$

$$|\Psi^+ >= \frac{1}{\sqrt{2}}(|0>_A \otimes |1>_B + |1>_A \otimes |0>_B)$$

$$|\Psi^- >= \frac{1}{\sqrt{2}}(|0>_A \otimes |1>_B - |1>_A \otimes |0>_B)$$

How Quantum Teleportation Works

The whole system

$$CAB = |\psi > \otimes |\Phi^+ >$$

$$= \frac{1}{\sqrt{2}}(\alpha|0> + \beta|1>) \otimes (|0>_A \otimes |0>_B + |1>_A \otimes |1>_B)$$

Recombining in Bell's basis

$$CAB = \tfrac{1}{2}|\Phi^+ > \otimes (\alpha|0> + \beta|1>)$$

$$+ \tfrac{1}{2}|\Phi^- > \otimes (\alpha|0> - \beta|1>)$$

$$+ \tfrac{1}{2}|\Psi^+ > \otimes (\beta|0> + \alpha|1>)$$

$$+ \tfrac{1}{2}|\Psi^- > \otimes (-\beta|0> + \alpha|1>)$$

How Quantum Teleportation Works

Alice measures her pair CA.
Obtains one of $|\Phi^+>$, $|\Phi^->$, $|\Psi^+>$, $|\Psi^->$,

Now Bob's qubit is respectively one of
$(\alpha|0> +\beta|1>)$, $(\alpha|0> -\beta|1>)$, $(\beta|0> +\alpha|1>)$, $(-\beta|0> +\alpha|1>)$.
Alice tells Bob by conventional channel the result of her measurement, so Bob knows what he has.
If his qubit is
$(\alpha|0> +\beta|1>)$: do nothing ($\equiv$ multiply by I)
$(\alpha|0> -\beta|1>)$: multiply by $Z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$
$(\beta|0> +\alpha|1>)$: multiply by $X = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$
$(-\beta|0> +\alpha|1>)$: multiply by $iY = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$
And he gets the original qubit C.

How Quantum Teleportation Works

History of Quantum Teleportation

- Original proposal:
Charles H. Bennett, Gilles Brassard, Claude Crepeau, Richard Jozsa, Ashes Peres, and William K. Wootters, Phys. Rev. Lett. 70, 1895 (March 29,1993)

- Established protocol of quantum teleportation

History of Quantum Teleportation

- Anton Zeilinger: Quantum Teleportation of photons

- Experiments with photons:
D. Bouwmeester, J.-W. Pan, K. Mattle, M. Eibl, H. Weinfurter, A. Zeilinger, Experimental Quantum Teleportation, Nature 390, 6660, 575-579 (1997).

History of Quantum Teleportation

- Experiments with atoms/ions:

S. Olmschenk, D. N. Matsukevich, P. Maunz, D. Hayes, L.-M. Duan, and C. Monroe, Quantum Teleportation between Distant Matter Qubits, Science 323, 486 (2009).

M. Riebe et al, Deterministic Quantum Teleportation with Atoms, Nature 429, 734-737 (2004)

M. D. Barrett et al, Deterministic Quantum Teleportation of Atomic Qubits, Nature 429, 737 (2004).

Quantum Teleportation Between Distant Matter Qubits

Science 323, 486 (2009)

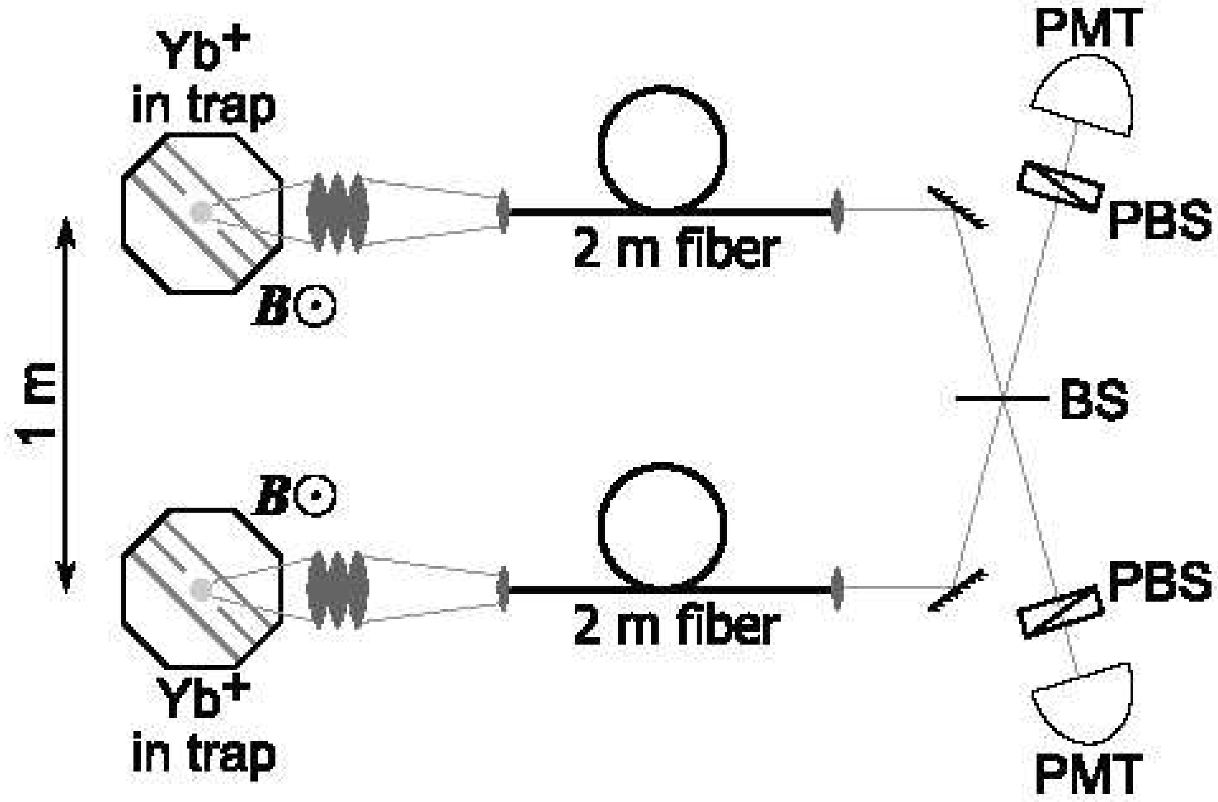

Fig. 1. The experimental setup. Two Yb^+ ions are trapped in independent vacuum chambers. An externally applied magnetic field ***B*** determines a quantization axis for defining the polarization of photons emitted by each atom. Spontaneously emitted photons are collected with an objective lens, coupled into a single-mode fiber, and directed to interfere on a beamsplitter (BS). Polarizing beamsplitters (PBSs) filter out photons resulting from σ decays in the atoms. The remaining π-polarized photons are detected by single-photon counting PMTs.

- Teleportation of state between 2 Yb^+ ions.

Quantum Teleportation Between Distant Matter Qubits

Science 323, 486 (2009)

- A, B - 2 Yb^+

2 hyperfine states

$^2S_{1/2}|F=0, m_F=0>\equiv|0>$, $^2S_{1/2}|F=1, m_F=0>\equiv|1>$

1) Initialized with laser beams:

$|\Psi(t_1)>_A = \alpha|0> + \beta|1>$ - qubit with information to transfer

$|\Psi(t_1)>_B = \frac{1}{\sqrt{2}}(|0> + |1>)$

2) Pumped with laser into excited state:

$|0> \rightarrow {}^2P_{1/2}|F=1, m_F=0>$

$|1> \rightarrow {}^2P_{1/2}|F=0, m_F=0>$

3) Excited states emit photons ν_{red}, ν_{blue} depending on state:

$|\Psi(t_2)>_A = \alpha|0>_A|\nu_{blue}>_A + \beta|1>_A|\nu_{red}>_A$

$|\Psi(t_2)>_B = \frac{1}{\sqrt{2}}(|0>_B|\nu_{blue}>_B + |1>_B|\nu_{red}>_B)$

4) Photons go through beamsplitter

Quantum Teleportation Between Distant Matter Qubits

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5) Photons simultaneously detected by single-photon counters; can only happen when

$|\Psi^- >_{photons} = \frac{1}{\sqrt{2}}(|\nu_{blue} >_A |\nu_{red} >_B - |\nu_{red} >_A |\nu_{blue} >_B)$

Which makes ions entangled:

$$< \Psi^-(t_3)|_{photons}(|\Psi(t_3) >_A \otimes |\Psi(t_3) >_B)$$

$$= |\Psi^-(t_3) >_{ions} = \frac{1}{\sqrt{2}}(\alpha|0 >_A |1 >_B - \beta|1 >_A |0 >_B)$$

(Here not quite clear to me. I think we are almost done. To recover the original qubit, we may apply to B rotation $R_y(\pi)$, and we'll get

$|\Psi >_B = \alpha|0 >_B + \beta|1 >_B$,

still entangled with A.

But the authors proceed with a few more steps.)

Quantum Teleportation Between Distant Matter Qubits

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6) Rotation $R_y(\pi/2)$ applied to ion A:

$$|\Psi^-(t_4)>_{ions}=\frac{1}{2}(\alpha(|0>_A+|1>_A)|1>_B-\beta(-|0>_A+|1>_A)|0>_B)$$

7) State of A measured

8) Measurement of A projects B in a state:

$|\Psi(t_5)>_B=\alpha|1>_B+\beta|0>_B$ if measured $|0>_A$

$|\Psi(t_5)>_B=\alpha|1>_B-\beta|0>_B$ if measured $|1>_A$

Quantum Teleportation Between Distant Matter Qubits

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9) To recover the original qubit:

Apply to B rotation $R_x(\pi)$ if measured $|0>_A$

Apply to B rotation $R_y(\pi)$ if measured $|1>_A$

$|\Psi(t_6)>_B = \alpha|0>_B + \beta|1>_B$

Teleportation accomplished: B now is in the original state of A.

Quantum Teleportation Between Distant Matter Qubits

Science **323**, 486 (2009)

- Protocol used differ from the original proposal:

- C - 4 qubits instead of 3

- Probabilistic character: number of attempts $\sim 10^8$.

Still, impressive achievement.

Quantum Teleportation

Summary

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