Implementation of Quantum Information Processing with Atomic Ensembles

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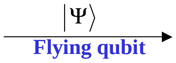
Duan, Lukin, Cirac, Zoller, Nature 414, 413-418 (2001)
-- for long-distance quantum communication
Duan, Phys. Rev. Lett. 88, 170402 (20002).
-- for many-party entanglement

Quantum communication

- Purpose and applications
  - ➢ Secret communication via quantum cryptography
  - ➢ Transfer of quantum information (teleportation)
  - ➢ Detection of quantum nonlocality via Bell inequalities

General requirements for Implementation

- Implementation of quantum communication
  - Flying qubits (photons)
  - Scalable to long distance



- Difficulty:

--fidelity: state distorted by channel noise

--efficiency: photons will be absorbed after the attenuation length!

$$P \propto e^{-L/L_{att}} \qquad L_{att} \approx \text{ km}$$

- Solution:
  - ❖ Classically, amplify and correct signals through repeaters
  - ❖ Quantum repeaters in quantum case (different principle!)

Quantum communication: central task

- Central task of communication -- generation of distant EPR states

EPR (Maximally entangled) states

$$|\Psi_{EPR}\rangle = |h,v\rangle_{LR} + |v,h\rangle_{LR}$$

via it

State transfer by teleportation

QKD by Ekert scheme

Bell inequality detection

- How to generate distant EPR state?

Quantum repeaters (Briegel et al, PRL 98)

1. Solve the Fidelity problem

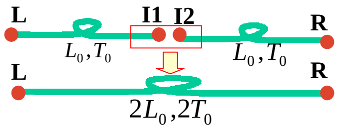
$$F = {}_{LR}\langle\Psi|\rho_{LR}|\Psi\rangle_{LR} < 1$$

$$F < 1 \xrightarrow[\text{purification}]{\text{entanglement}} F \uparrow 1,\ p_{succ} \downarrow \propto e^{-L/L_{att}},\ T \propto e^{L/L_{att}}$$

2. Solve the efficiency problem

Entanglement connection

$$T_0 \propto e^{L_0/L_{att}}$$



Efficiency in ideal case $T \propto e^{L/L_{att}} \rightarrow T \propto (L/L_0)T_0$

Imperfect connection → **Below threshold noise, polynomial**

Implementation of quantum repeaters

- **Implementation of quantum repeaters:**
  - **Storage qubits (atomic internal states, …)**
  - **Entangling storage qubits via flying qubits**
  - **Local collective operations on storage qubits**

- **One possibility:**
  - **trapped single atoms in high-Q cavities**
  - **strong light-atom interaction through cavity QED**

Advantages with atomic ensembles

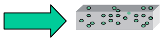
- Much simplified experimental technology
- Collectively enhanced coupling to light.
- Simple collective operation through linear optics and feedback
- Inherently robust to realistic noise

Outline of the proposal

- Entanglement generation between atomic ensembles
- Entanglement connection to extend commun. distance
- Entanglement-based communication
- Inherently robust to noise and imperfections
- Scaling of the communication efficiency

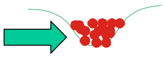
Entanglement generation: basic system

Experimental candidates of atomic ensembles



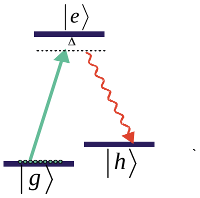
Room-temperature gas

Glass cell



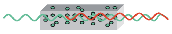
Cold trapped atom

MOT

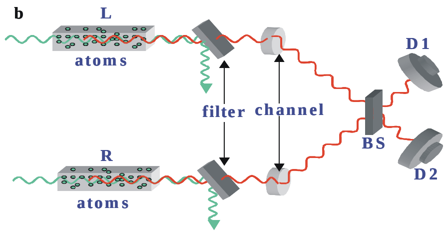


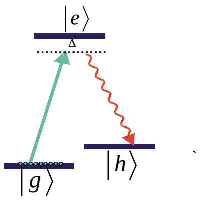
Collective atomic mode $h^{+} = \left(1/\sqrt{N_a}\right)\sum_i |h\rangle_i \langle g|$

Forward scattered pulse mode
(Signal mode) a



Entanglement generation

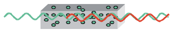




- **Steps:**
  1. **Apply a short green laser pulse on each ensemble, with the signal photon number** $\langle n_s \rangle << 1$
  2. **Succeeds if D1 or D2 registers one photon, finished!**
  3. **Fails otherwise, and go to step 1.**

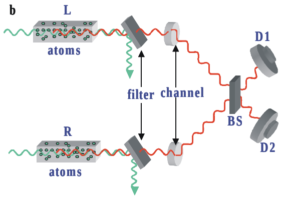
Entanglement generation

- **Generated state**



$$|\phi\rangle = |0_a\rangle|0_p\rangle + \sqrt{p_c}\, h^+ a^+ |0_a\rangle|0_p\rangle + o(p_c)$$

$$p_c << 1$$

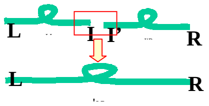


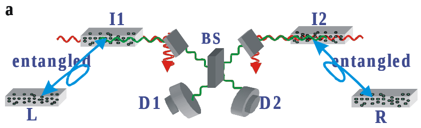
$$\begin{aligned} |\Psi\rangle_{LR} &= \langle 0_p 0_p | (a_L \pm a_R) |\phi\rangle \otimes |\phi\rangle \\ &= (h_L^+ \pm h_R^+)|0_a 0_a\rangle_{LR} \\ &= |0_a, 1_a\rangle_{LR} \pm |1_a, 0_a\rangle_{LR} \end{aligned}$$

Maximally entangled
in the number basis!

Entanglement connection

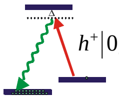
- **Principle setup** **Schematic real setup**





- **Steps:**

1. **apply a red laser pulse to transfer atomic excitation to optical exc.**



$$h^+|0_a\rangle \to a^+|0_p\rangle$$

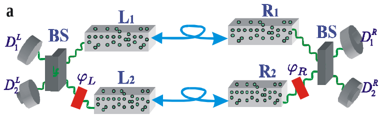
2. **succeeds if D1 or D2 registers one photon**

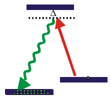
$$(h_L^+ + h_I^+)(h_{I'}^+ + h_R^+)|0000\rangle \Longrightarrow |\Psi\rangle_{LR} = (h_L^+ + h_R^+)|00\rangle \quad \text{(ideal case)}$$

3. **fails otherwise, and repeat every step from entanglement generation.**

Entanglement-based communication

- Schematic setup for QKD and Bell inequality detection





- Steps:

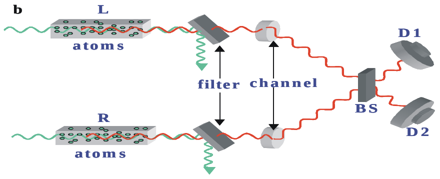
1. Transfer atomic excitation to optical exc., detect after phase shifter and BS
2. Succeeds if one photon is registered from left and one photon from right.

$$\left(h_{L1}^{+}+h_{R1}^{+}\right)\left(h_{L2}^{+}+h_{R2}^{+}\right)|0000\rangle \Rightarrow |\Psi_{PME}\rangle=\left(h_{L1}^{+}h_{R2}^{+}+h_{L2}^{+}h_{R1}^{+}\right)|0000\rangle$$

3. Role of $\varphi_{L,R}$: single-bit rotation in polarization (spin) basis $\begin{cases} h_1^{+}|0_a\rangle \\ h_2^{+}|0_a\rangle \end{cases}$

Robust to noise

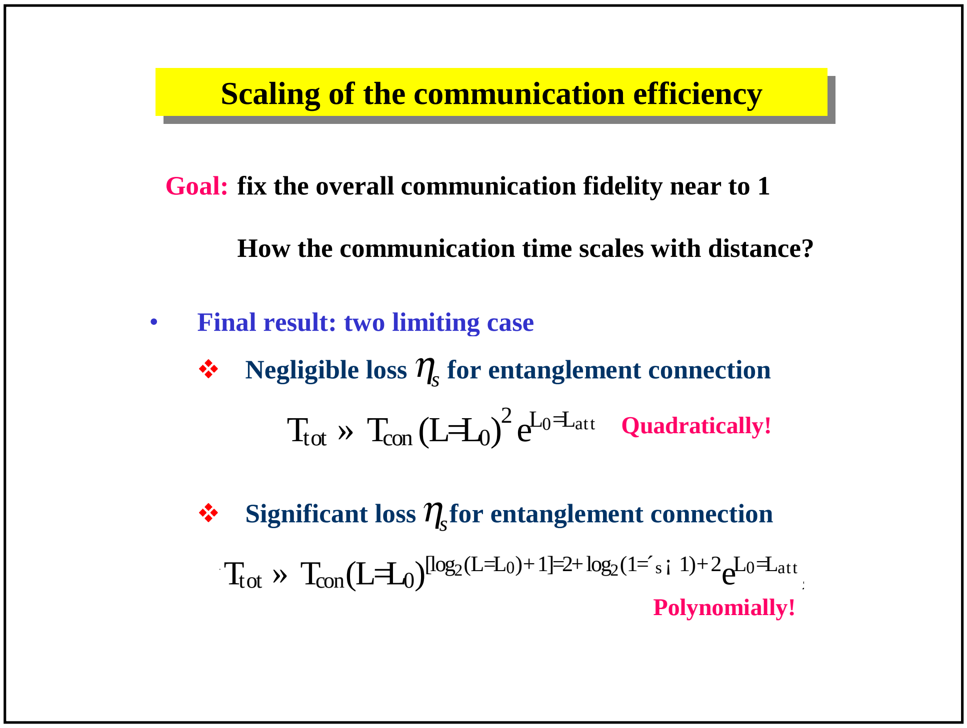
- Noise in entanglement generation



Loss
- Spontaneous emission
- Channel attenuation
- Detector inefficiency

→ Decrease efficiency

$|\Psi\rangle_{LR}=\left(h_L^{+}+h_R^{+}\right)|00\rangle$ remains unchanged!



Scaling of the communication efficiency

Goal: **fix the overall communication fidelity near to 1**

How the communication time scales with distance?

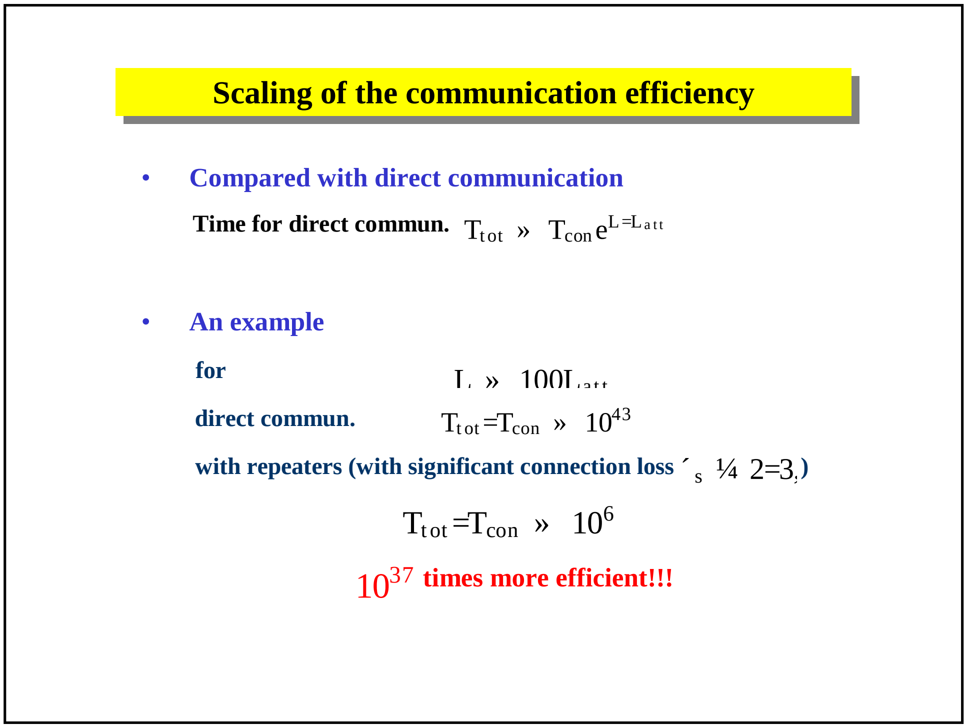
- **Final result: two limiting case**
  - **Negligible loss η_s for entanglement connection**

$$T_{tot} \approx T_{con} (L/L_0)^2 e^{L_0/L_{att}}$$ **Quadratically!**

  - **Significant loss η_s for entanglement connection**

$$T_{tot} \approx T_{con} (L/L_0)^{[\log_2(L/L_0)+1]/2+\log_2(1/\eta_s - 1)+2} e^{L_0/L_{att}}$$

Polynomially!



Scaling of the communication efficiency

- **Compared with direct communication**

Time for direct commun. $T_{tot} \approx T_{con} e^{L/L_{att}}$

- **An example**

for $L \approx 100 L_{att}$

direct commun. $T_{tot}/T_{con} \approx 10^{43}$

with repeaters (with significant connection loss $\eta_s \approx 2/3$**)**

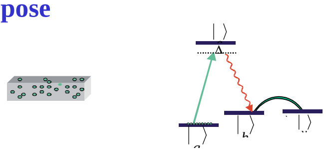
$$T_{tot}/T_{con} \approx 10^6$$

10^{37} **times more efficient!!!**

- ➢ Long-distance quantum communication with atomic ensembles
- ➢ Many-party entanglement between atomic ensembles

Many-party entanglement generation: motivation

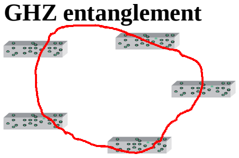
- Purpose



Polarization (spin) qubits

$$\begin{cases} h^{+}\left|0_{a}\right\rangle \\ v^{+}\left|0_{a}\right\rangle \end{cases}$$

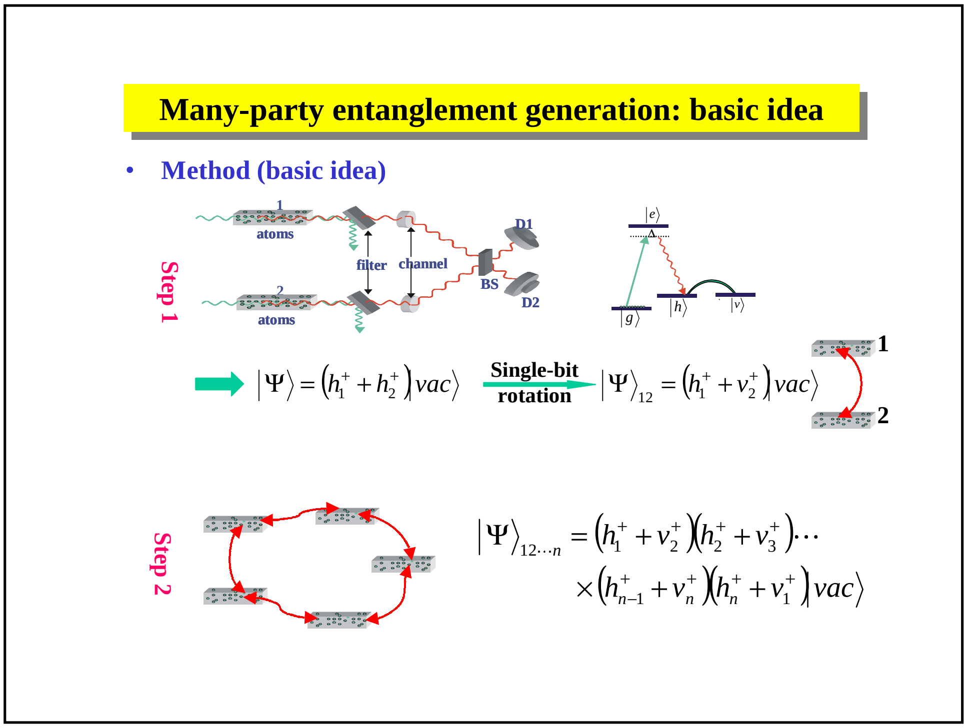
GHZ entanglement



$$\left|\Psi_{GHZ}\right\rangle = \left(h_1^{+} h_1^{+} \cdots h_n^{+} + v_1^{+} v_2^{+} \cdots v_n^{+}\right)\left|vac\right\rangle$$

$$\left|vac\right\rangle = \left|0_1 0_2 \cdots 0_n\right\rangle$$

- Applications of many-party entanglement
  - ➢ Sharp test of quantum nonlocality (GHZ, Mermin)
  - ➢ High-precision spectroscopy (Wineland et al.)
  - ➢ Building block of quantum computation (Gottesman, Chuang)

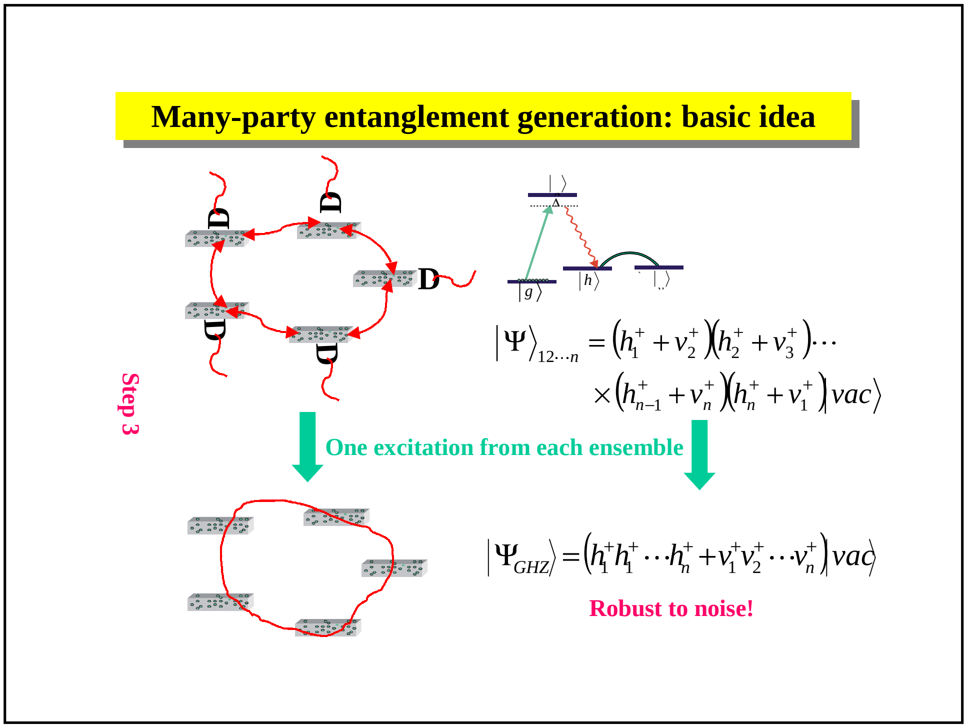


Many-party entanglement generation: basic idea

- Method (basic idea)

$$|\Psi\rangle = (h_1^+ + h_2^+)|vac\rangle \xrightarrow{\text{Single-bit rotation}} |\Psi\rangle_{12} = (h_1^+ + v_2^+)|vac\rangle$$

$$|\Psi\rangle_{12\cdots n} = (h_1^+ + v_2^+)(h_2^+ + v_3^+)\cdots \times (h_{n-1}^+ + v_n^+)(h_n^+ + v_1^+)|vac\rangle$$



Many-party entanglement generation: basic idea

$$|\Psi\rangle_{12\cdots n} = (h_1^+ + v_2^+)(h_2^+ + v_3^+)\cdots \times (h_{n-1}^+ + v_n^+)(h_n^+ + v_1^+)|vac\rangle$$

One excitation from each ensemble

$$|\Psi_{GHZ}\rangle = (h_1^+ h_1^+ \cdots h_n^+ + v_1^+ v_2^+ \cdots v_n^+)|vac\rangle$$

Robust to noise!

Many-party entanglement generation: efficiency

$$\left|\Psi\right\rangle_{12\cdots n} = \left(h_1^+ + v_2^+\right)\left(h_2^+ + v_3^+\right)\cdots \times \left(h_{n-1}^+ + v_n^+\right)\left(h_n^+ + v_1^+\right)\left|vac\right\rangle \xrightarrow[(\eta/2)^n]{\text{efficiency}} \left|\Psi_{GHZ}\right\rangle = (h_1^+ h_1^+ \cdots h_n^+ + v_1^+ v_2^+ \cdots v_n^+)\left|vac\right\rangle$$

Inefficient!

- **Improved scheme:**

Preparation time $T = t_0\left[2\eta n/(1-\eta)^2\right](n/2)^{\log_2\left[2\eta\sqrt{n}/(1-\eta)^2\right]}$

efficient!

- **Example:**

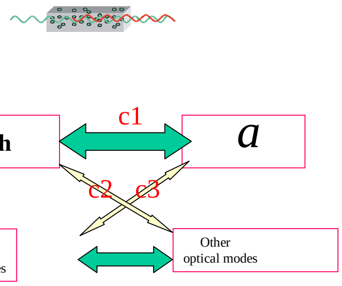
$$\left.\begin{aligned} n &= 16 \\ \eta &= 1/3 \\ t_0 &= 10\,\mu s \end{aligned}\right\} \Longrightarrow T = 50\,ms$$

Current exp. record: $n = 4$

Summary

- ❖ **atomic ensembles: promising candidates for QIP with**
  - **simplified experimental technology**
  - **strong coupling to light**
  - **inherent fault-tolerance**
  - **efficient**
- ❖ **Long-distance quantum communication**
- ❖ **Many-party entanglement**

Interaction picture



h

c1

a

c2

c3

Other atomic modes

Other optical modes