Quantum Networks

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What is a quantum network ?

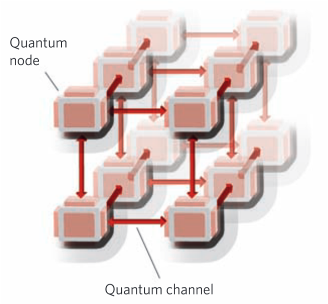

Figure 1: Principle of a quantum network. [1]

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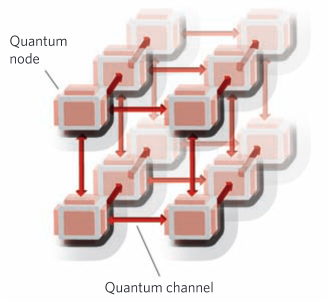

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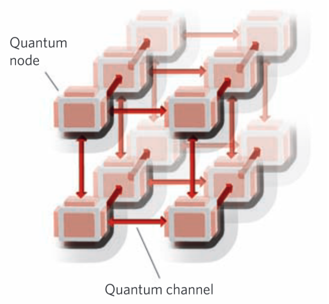

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- Many body simulations
- Bigger state space

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Increase the state space

- Classical connectivity between 2 nodes consisting of n qubits.

$$|u_0\rangle_1 \otimes |u_0\rangle_2 \xrightarrow{U_1,U_2} U_1|u_0\rangle_1 \otimes U_2|u_0\rangle_2$$

$$\sum_{i=0}^{2^n-1} \alpha_i|u_i\rangle_1 \otimes \sum_{j=0}^{2^n-1} \beta_j|u_j\rangle_2 \ \rightarrow \text{dimension} = 2 \cdot 2^n$$

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- Quantum connectivity :

$$|u_0\rangle_1 \otimes |u_0\rangle_2 = |u_0, u_0\rangle \xrightarrow{U} U|u_0, u_0\rangle$$

$$\sum_{i=0}^{2^n-1} \sum_{j=0}^{2^n-1} \gamma_{i,j}|u_i, u_j\rangle \rightarrow \text{dimension} = (2^n)^2 = 2^{2n}$$

Photons for quantum channels

- Advantages
  - Low interaction with environment
  - Fast carrier
- Drawbacks
  - Single photon → low coupling at the node

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Solutions :

- Enhance coupling with a cavity
- Ensemble of many atoms as nodes ($\sqrt{n}$ enhancement)

Key characteristics of channel ↔ node interaction

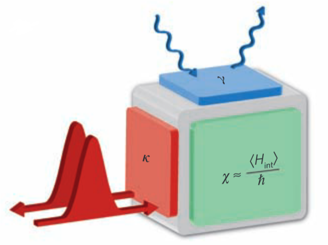

Figure 2: Different rates at a node : χ = coherent coupling, κ = bandwidth of the input-output channel and γ = parasitic losses. We need $\chi > \kappa \gg \gamma$.[3]

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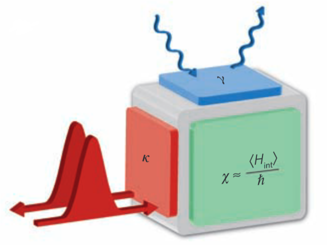

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Single atom in a cavity : $\chi = g$ = Rabi frequency, κ = decay rate of the cavity mode into the channel and γ = atomic decay rate.

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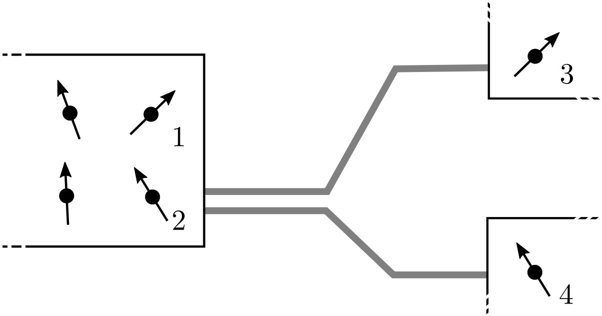
Remote qubit error-correction



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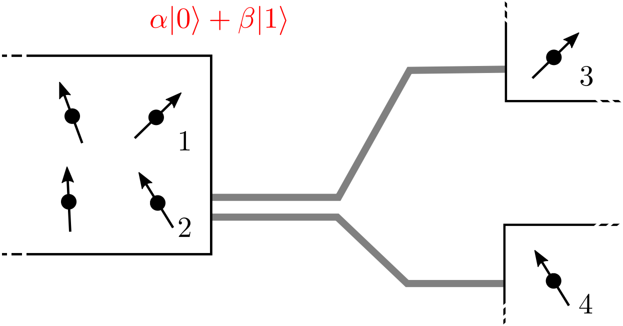
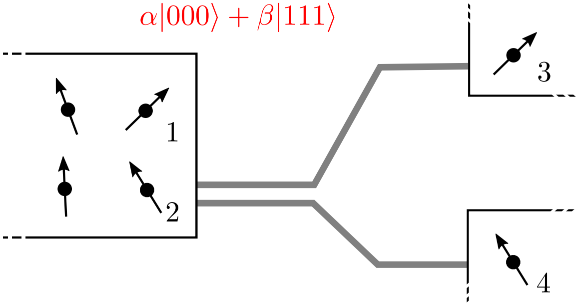


Remote qubit error-correction

$\alpha|000\rangle + \beta|111\rangle$



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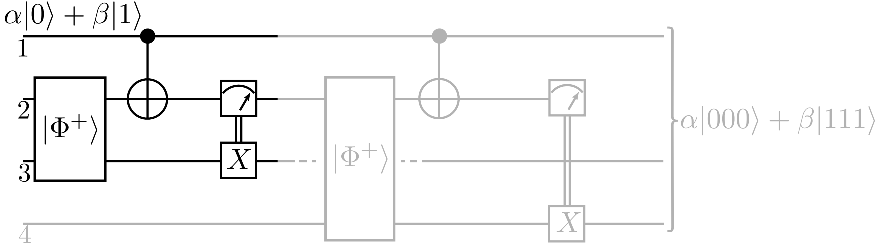

$\alpha|0\rangle + \beta|1\rangle \otimes \frac{1}{\sqrt{2}}|00\rangle + |11\rangle$

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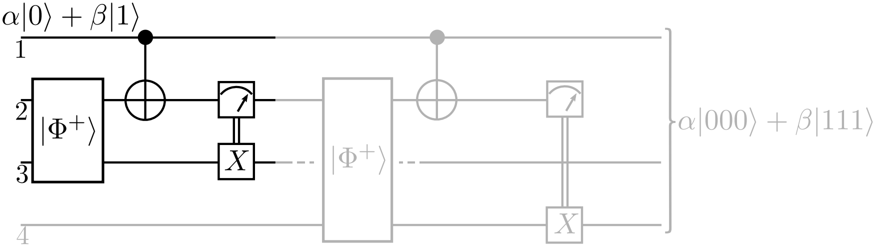

$$\alpha|0\rangle + \beta|1\rangle \otimes \frac{1}{\sqrt{2}}|00\rangle + |11\rangle \xrightarrow{C_{NOT}} \frac{\alpha}{\sqrt{2}}\left(|000\rangle + |011\rangle\right) + \frac{\beta}{\sqrt{2}}\left(|110\rangle + |101\rangle\right)$$

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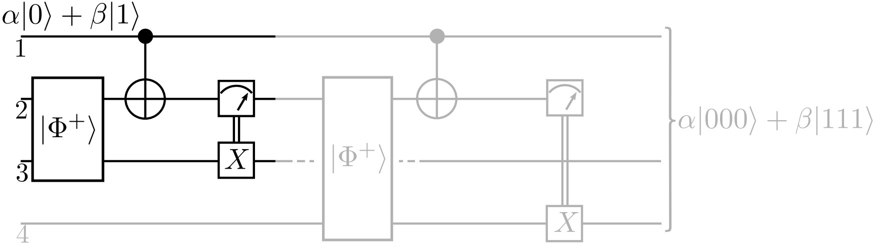

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If qubit 2 is 0 : $\alpha|0_1 0_3\rangle + \beta|1_1 1_3\rangle \rightarrow$ ok

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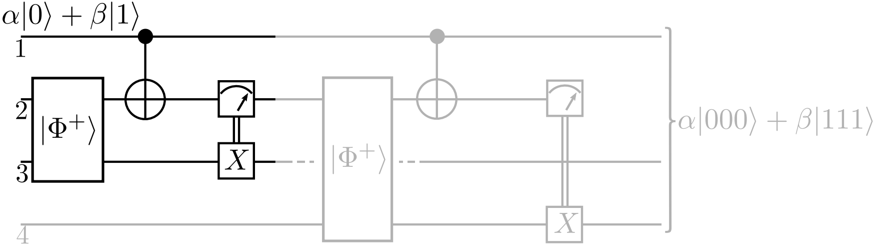

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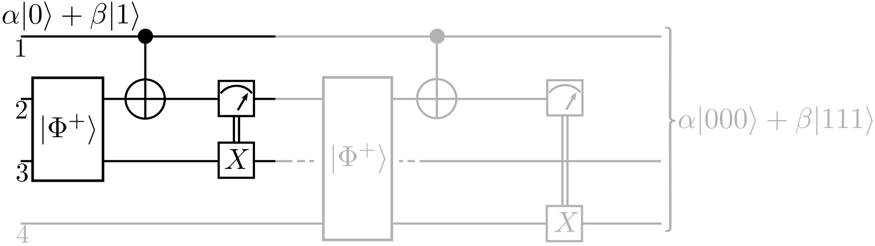

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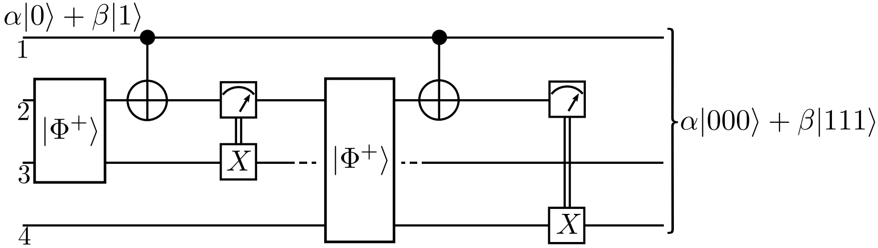
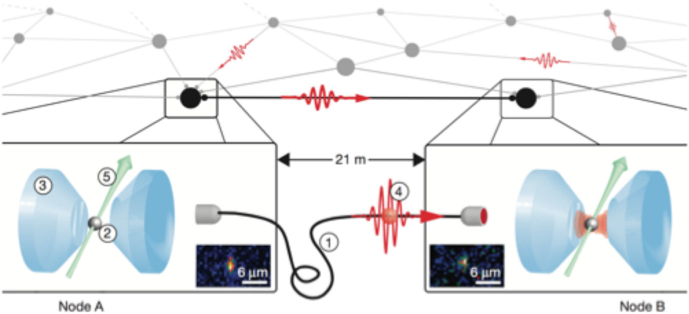
Remote qubit error-correction



$\alpha|0_1\rangle + \beta|1_1\rangle \rightarrow \alpha|0_1 0_3 0_4\rangle + \beta|1_1 1_3 1_4\rangle$
with qubit 3 & 4 remote.

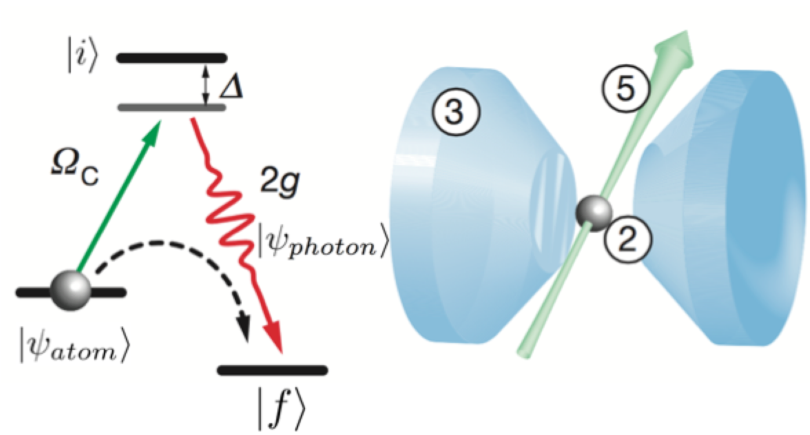
Summary of Experiments

Goal: Demonstrate two functioning quantum network nodes in independent laboratories.



$$|\psi_{atom}\rangle \longrightarrow |\psi_{photon}\rangle \longrightarrow |\psi_{atom}\rangle$$

The Quantum Network Node



Ritter et al. 2012 [2]

Linking Nodes

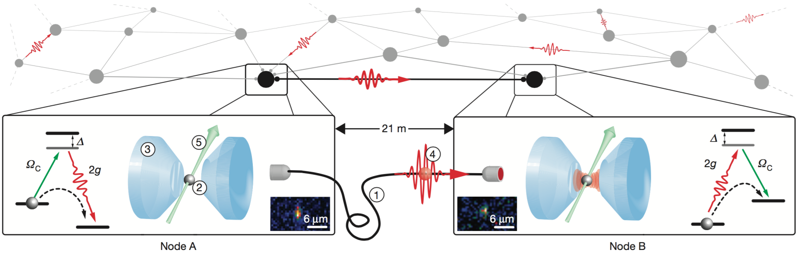
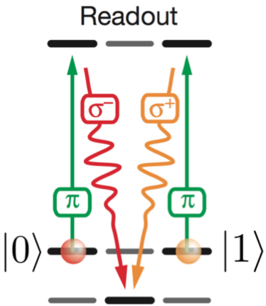


Figure 3: **1.** Optical fiber link (60m) **2.** Rb atom in dipole trap **3.** High-finesse optical cavity **4.** single photon wavepacket **5.** control laser.

Quantum State Conversion

- σ^- and σ^+ photons excite atomic state to $m = -1$ and $m = +1$ states, respectively.
- control laser applies π-polarized pulse, sending the atomic states between different Zeeman Manifolds.
- atomic qubit: $|m = \pm 1\rangle$
- photonic qubit: $|\sigma = \pm 1\rangle$



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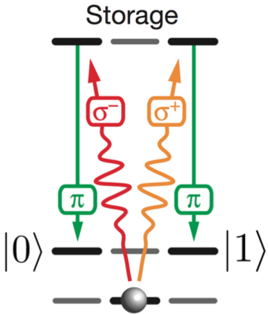

Experimental results

The authors achieve to construct the basic elements of a quantum network

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1. Initialization of qubits in an arbitrary state
2. State transfer
3. Entanglement distribution (long storage time)
4. Perform local operations to create different entangled atomic bipartite states

Implications of results

- Tailorable topology

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- Tailorable topology
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- Quantum Communication network
- Quantum Many-body simulation
- Distributed quantum information processing

Drawbacks

The author's realization of a simple quantum 2-node/1-link network is a proof of principle but has drawbacks that have to be overcome

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1. Improve coupling to increase success probability of write-readout process
2. Typical ND-measurement in trapped ions require non-degenerate energy levels
3. logical states are not insensitive to residual magnetic fields

Conclusions

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    - Quantum nodes linked by a quantum channel
    - State transfer & entanglement distribution
    - Long lifetime of shared entanglement
2. Doubts on scalability of such network implementation
3. Still far away from a functioning quantum network

Bibliography

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