Cavity QED with Neutral Atoms

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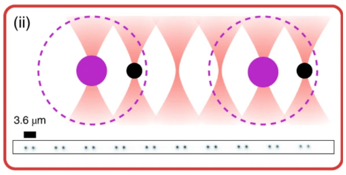
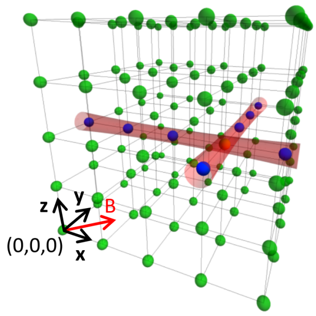
Atoms as Qubits

- Nature's qubit
- Intrinsically identical
- Coherence control between two energy levels of an atom - Atomic clock

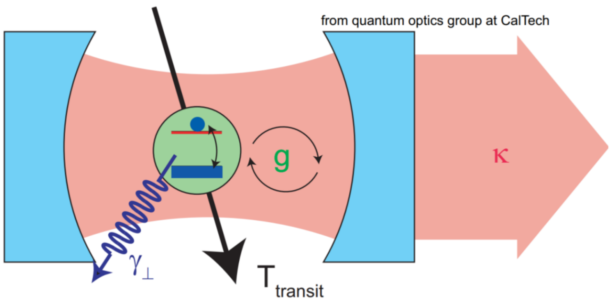


Caltech *Nat. Phys. 16, 857-861 (2020)*



Penn state *Y. Wang et al., Phys. Rev. Lett. (2015)*

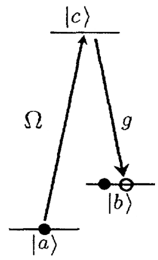
Two level system



- Atom - cavity interaction rate, g
- Cavity loss rate κ
- Atomic transition loss γ
- Transit time **T**

Three level system

- $\Omega(t)$ is the laser driven interaction
- g is fixed
- Individually switch on/off $|a\rangle \to |c\rangle$ transition
- $|a\rangle|0\rangle \to |b\rangle|1\rangle$ is an adiabatic passage



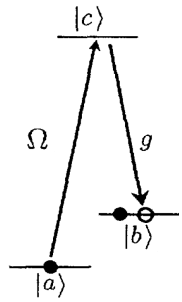
Λ configuration

Dark State Adiabatic Passage

- Eigen states of the Hamiltonian
- Decoupled from the excited states by quantum interference
- Immune to spontaneous emission as $|a\rangle$ and $|b\rangle$ are ground states

Dark State of a Three-level atom

- $|D_0\rangle = |b\rangle|0\rangle$
- $|D_1\rangle \propto g|a\rangle|0\rangle + \Omega(t)|b\rangle|1\rangle$
- No terms from $|c\rangle$
- $g/\Omega(t) \to 0$, $|a\rangle|0\rangle$ may adiabatically transform to $|b\rangle|1\rangle$



Quantum Computing

- First proposal to use neutral atom - cavity interaction for quantum computing
- Cavity decay minimised by a photon present only during gate operation

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Decoherence, Continuous Observation, and Quantum Computing: A Cavity QED Model

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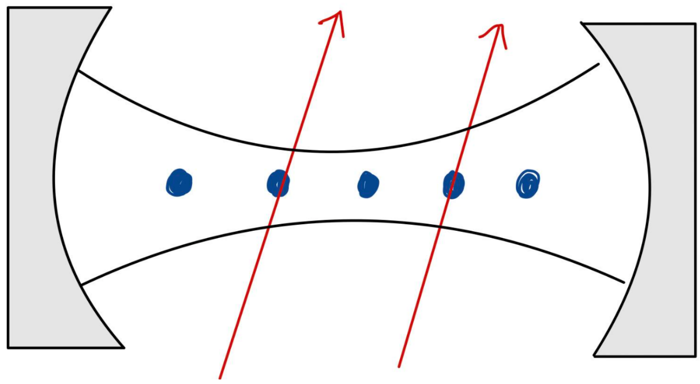
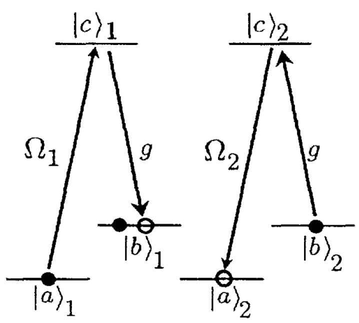
(Received 27 June 1995)

We use the theory of continuous measurement to analyze the effects of decoherence on a realistic model of a quantum computer based on cavity QED. We show how decoherence affects the computation, and methods to prevent it.

Setup

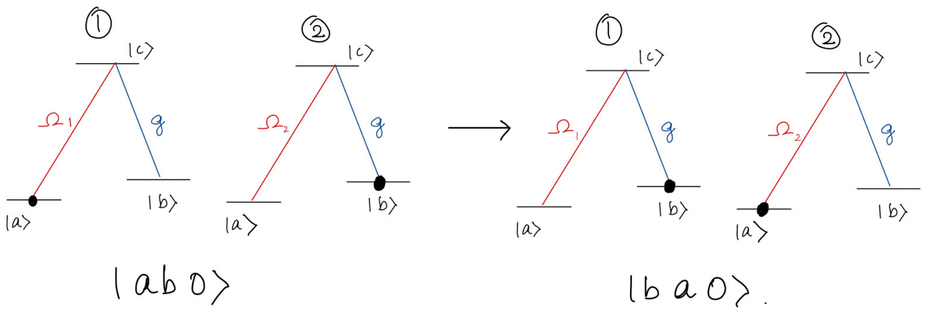


Two Atoms in the Cavity



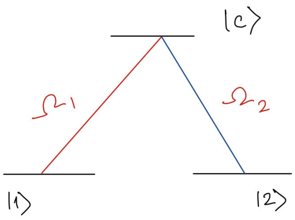
- $|b\rangle_j \rightarrow |c\rangle_j$ coupled to same quantised cavity mode
- $|a\rangle_j \rightarrow |c\rangle_j$ coupled to coherent driving field
- $H_I = \sum_{j=1,2}\left(\frac{\Omega_j(t)e^{-i\omega_L t}}{2}|c\rangle_{jj}\langle a| + \frac{g}{2}|c\rangle_{jj}\langle b|\hat{b}\right)$

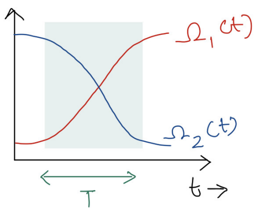
Dark State



- $|D_0\rangle = |b\rangle_1|b\rangle_2|0\rangle \equiv |b, b, 0\rangle$
- $|D_1\rangle \propto \Omega_1(t)g|b, a, 0\rangle + \Omega_2(t)g|a, b, 0\rangle - \Omega_1\Omega_2|b, b, 1\rangle$
- No contribution from $|c\rangle_j \rightarrow$ no spontaneous emission
- $|a\rangle_1|b\rangle_2|0\rangle_c \xrightarrow{\Omega_1} |c\rangle_1|b\rangle_2|0\rangle_c \xrightarrow{g} |b\rangle_1|b\rangle_2|1\rangle_c \xrightarrow{g} |b\rangle_1|c\rangle_2|0\rangle_c \xrightarrow{\Omega_2}$ $|b\rangle_1|a\rangle_2|0\rangle_c$

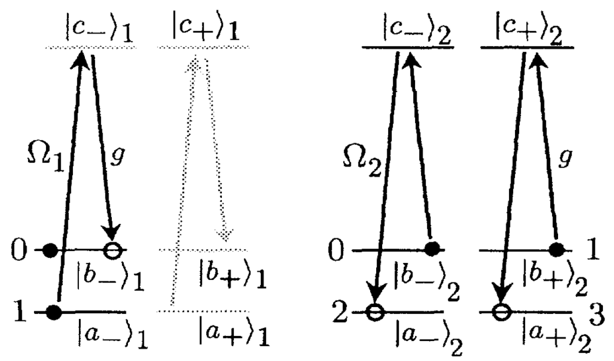
Adiabatic Passage





- Adiabaticity condition $\Omega T >> 1$
- Transfer coherence via superposition of $|D_0\rangle$ and $|D_1\rangle$, like $\Big(A|a\rangle_1 + B|b\rangle_1\Big)|b\rangle_2|0\rangle_c \rightarrow |b\rangle_1\Big(A|a\rangle_2 + B|b\rangle_2\Big)|0\rangle_c$

CNOT Gate implementation



- Map two qubits to a single four level system in Atom 2
- Transform the state according to the CNOT gate operation
- Invert the first step

Truth Table

- $|1\rangle, |0\rangle = |a_-\rangle, |a_+\rangle$
- Interchange $|2\rangle$ and $|3\rangle$ by using a π pulse

$\lvert CT\rangle$	Two qubits	Single four-level system			Inverted	Output
$\lvert 00\rangle$	$\lvert a_+\rangle_1 \lvert a_+\rangle_2$	$\lvert 0\rangle$	$\lvert b_-\rangle_2$	$\lvert 0\rangle$	$\lvert a_+\rangle_1 \lvert a_+\rangle_2$	$\lvert 00\rangle$
$\lvert 01\rangle$	$\lvert a_+\rangle_1 \lvert a_-\rangle_2$	$\lvert 1\rangle$	$\lvert b_+\rangle_2$	$\lvert 1\rangle$	$\lvert a_+\rangle_1 \lvert a_-\rangle_2$	$\lvert 10\rangle$
$\lvert 10\rangle$	$\lvert a_-\rangle_1 \lvert a_+\rangle_2$	$\lvert 2\rangle$	$\lvert a_-\rangle_2$	$\lvert 3\rangle$	$\lvert a_-\rangle_1 \lvert a_-\rangle_2$	$\lvert 11\rangle$
$\lvert 11\rangle$	$\lvert a_-\rangle_1 \lvert a_-\rangle_2$	$\lvert 3\rangle$	$\lvert a_+\rangle_2$	$\lvert 2\rangle$	$\lvert a_-\rangle_1 \lvert a_+\rangle_2$	$\lvert 10\rangle$

Quantum Network

- Proposal to use Cavity QED to share entanglement among spatially distant atoms
- Avoid reflection of wave packet from the second cavity

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Quantum State Transfer and Entanglement Distribution among Distant Nodes in a Quantum Network

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[2]*Institut für Theoretische Physik, Universität Innsbruck, Technikerstrasse 25, A-6020 Innsbruck, Austria*
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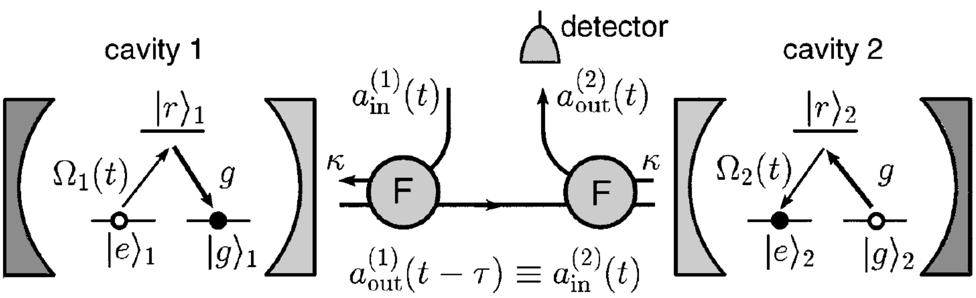
(Received 12 November 1996)

We propose a scheme to utilize photons for ideal quantum transmission between atoms located at *spatially separated* nodes of a quantum network. The transmission protocol employs special laser pulses that excite an atom inside an optical cavity at the sending node so that its state is mapped into a *time-symmetric* photon wave packet that will enter a cavity at the receiving node and be absorbed by an atom there *with unit probability*. Implementation of our scheme would enable reliable transfer or sharing of entanglement among spatially distant atoms. [S0031-9007(97)02983-9]

Two Atoms in Cavities



- Accomplish ideal quantum transmission (Coherence transfer)
- $\left(c_g|g\rangle_1 + c_e|e\rangle_1\right)|g\rangle_2 \otimes |0\rangle_1|0\rangle_2|vac\rangle \rightarrow$
  $|g\rangle_1\left(c_g|g\rangle_2 + c_e|e\rangle_2\right) \otimes |0\rangle_1|0\rangle_2|vac\rangle$
- Laser strongly detuned from atomic transition

- The output of each cavity is given by:
  $\hat{a}_{out}^{(1)}(t) = \hat{a}_{in}^{(1)}(t) + \sqrt{2\kappa}\hat{a}_1(t)$
  $\hat{a}_{out}^{(2)}(t) = \hat{a}_{in}^{(1)}(t-\tau) + \sqrt{2\kappa}[\hat{a}_1(t-\tau) + \hat{a}_2(t)]$
- Quantum Langevin equations:
  $\frac{\mathrm{d}\hat{a}_1}{\mathrm{d}t} = -i[\hat{a}_1, \hat{H}_1(t)] - \kappa\hat{a}_1 - \sqrt{2\kappa}\hat{a}_{in}^{(1)}(t)$
  $\frac{\mathrm{d}\hat{a}_2}{\mathrm{d}t} = -i[\hat{a}_2, \hat{H}_2(t)] - \kappa\hat{a}_2 - 2\kappa\hat{a}_{in}^{1}(t-\tau) - \sqrt{2\kappa}\hat{a}_{in}^{(1)}(t-\tau)$
- First equation decoupled from the second one $\rightarrow$ unidirectional cavities
- $|D_0\rangle = c_g|gg\rangle|00\rangle$
- $|D_1\rangle = c_e[\alpha_1(t)e^{-\phi_1(t)}|eg\rangle|00\rangle + \alpha_2(t)e^{-\phi_2(t)}|ge\rangle|00\rangle + \beta_1(t)|gg\rangle|10\rangle + \beta_2(t)|gg\rangle|01\rangle]$
- Symmetric pulse condition : $g_2(t) = g_1(-t)$

Summary

- Cavity facilitates the qubit-qubit interaction
- Cavity-atom interactions can be used to transfer entanglement over a distance