Enhancing Atomic Quantum Memory for Light

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Motivation

- Experimental achievements: long-distance atomic entanglement, quantum memory for light [Julsgaard et al., Nature 413, 400 (2001); ibid 432, 482 (2004).]

- What capacity can such a memory have?

- So far only single coherence out of many atomic internal states used. How to take advantage of more of them?

- How to improve efficiency of reading the information out of the memory?

- Can the process be simplified?
Experimental setup
Two different quantizations

$z$-quantization

\[ a_x = 2^{1/2} (a_x - i a_y) \]
\[ a_y = 2^{1/2} (a_x + i a_y) \]

$z$-quantization: Faraday rotation and Stark shift

Higher population

Stronger field

$x$-quantization

\[ a_x = 2^{1/2} (a_x - i a_y) \]
\[ a_y = 2^{1/2} (a_x + i a_y) \]

$x$-quantization: Raman transitions

Stronger field

Stronger Stark shift
QND coupling, \(x\)-quantization

For the \(x\) polarized \(a_x\) field at \(\omega_0\)
Atoms resonantly coupled to two \(y\)-polarized modes at \(\omega_0 \pm \Omega, \Omega \propto B\).

\[
\tilde{H}_{AF}^{(1)} = i\hbar \sum_m G_m^{(1)} a_x^\dagger (a_y + \sigma_{m+1,m}^{(x)} + a_y - \sigma_{m,m+1}^{(x)}) + h.c.,
\]

\[
G_m^{(1)} = \frac{\mu_0^2 E_0^2}{48 \hbar^2 \Delta} \sqrt{20 - m(m + 1)}, \quad E_0^2 = \frac{\hbar \omega_0}{2\epsilon_0 AcT}
\]
QND coupling

Define cosine and sine field components and quadratures:

\[ a_{yC} = \frac{1}{\sqrt{2}} (a_y^- + a_y^+) , \quad a_{yS} = \frac{1}{\sqrt{2}} (a_y^- - a_y^+) \]

\[ X_j = \frac{1}{\sqrt{2}} (a_j + a_j^\dagger) , \quad P_j = \frac{1}{i\sqrt{2}} (a_j - a_j^\dagger) \]

For atoms prepared in \(|F, m = -F\rangle\), define quadratures

\[ X_A = \frac{1}{\sqrt{2N_A}} \sum_{k=1}^{N_A} \left( \sigma_{-F,-F+1}^{(x,k)} + \sigma_{-F+1,-F}^{(x,k)} \right) , \]

\[ P_A = \frac{1}{i\sqrt{2N_A}} \sum_{k=1}^{N_A} \left( \sigma_{-F,-F+1}^{(x,k)} - \sigma_{-F+1,-F}^{(x,k)} \right) \]
**QND coupling**

For strong coherent $x$-polarized component $|\alpha_0\rangle$ the Hamiltonian reads

$$H_{\text{int}}^{(1)} = \hbar \kappa (P_C X_A + X_S P_A),$$

$$\kappa = -\frac{E_0^2 \mu_0^2 \sqrt{N_L N_A}}{12 \hbar^2 \Delta}, \quad N_L = |\alpha_0|^2$$

One can get Hamiltonians $\sim P_C X_A$ and $X_S P_A$ separately using two atomic cells:
Employing additional sidebands

- Superpositions of $|m_F\rangle_x$ and $|m_F + k\rangle_x$ oscillate at $k\Omega$

- Is there modulation of Faraday rotation at $k\Omega$?

- How to couple the $|m_F\rangle_x$, $|m_F + k\rangle_x$ superpositions to the $k\Omega$ sidebands?
Employing additional sidebands

Apply additional circularly polarized field, near 2-photon resonant to the other HF level, $\omega_c - \omega_0 = \Delta_{\text{HF}} - \delta$: breaking the $R - L$ symmetry.

Employing additional sidebands

In the $x$ quantization: 4 photon Raman transitions:
Employing additional sidebands

After adiabatic elimination, hamiltonian:

\[
H_{AF}^{(2)} = i\hbar \sum_m G_m^{(2)} a_x a_c a_c^\dagger a_y 2 + \sigma_{m+2,m}^{(x)} + i\hbar \sum_m G_m^{(2)} a_x a_c a_c^\dagger a_y 2 - \sigma_{m,m+2}^{(x)} + h.c.
\]

\[
G_m^{(2)} = \frac{E_0^2 E_c^2 M_m^{(4)}}{\hbar^4 \delta_{m\pm} \Delta^2}.
\]

For cesium with \( F = 4 \)

\[
M_m^{(4)} = -\frac{\mu_0^4}{48^2} \sqrt{(3-m)(4-m)(5+m)(6+m)}
\]

\[
\delta_{m\pm} = \delta + \frac{\mu_0^2}{3\hbar^2 \Delta} (E_x^2 - E_c^2) + (2m + 2 \pm 1)\Omega
\]
Squeezer-like and beam-splitter-like interaction

Interaction type depends on two-photon detuning:

- If $2\Omega \ll |\delta'_m|$, then $G^{(2)}_{m+} \approx G^{(2)}_{m-} \rightarrow$ QND-type interaction

- If $|\delta'_{m;-}| \ll |\delta'_{m;+}|$, then dominant part is

  $$H^{(2,\text{SQ})}_{AF} = i\hbar G^{(2)}_{\text{SQ}}|\alpha_c|^2 \left( a_{y2-}\sigma_2^- - a_{y2-}^\dagger \sigma_2^+ \right),$$

  Squeezer-like interaction

- If $|\delta'_{m;-}| \gg |\delta'_{m;+}|$, then dominant part is

  $$H^{(2,\text{BS})}_{AF} = i\hbar G^{(2)}_{\text{BS}}|\alpha_c|^2 \left( a_{y2+}\sigma_2^+ - a_{y2+}^\dagger \sigma_2^- \right),$$

  Beam-splitter-like interaction.
Defining collective atomic modes associated with coherences between magnetic levels $m = -F$ and $m = -F + 2$,

$$ a_{A2} = \frac{1}{\sqrt{N_A}} \sum_{k=1}^{N_A} \sigma^{(x,k)}_{-F;-F+2}, $$

the hamiltonians summed over all atoms are

$$ H_{int}^{(2,SQ)} = i \hbar \kappa^{(2)} (a_{A2}^{\dagger} a_{y2}^{\dagger} - a_{A2} a_{y2}), $$

$$ H_{int}^{(2,BS)} = i \hbar \kappa^{(2)} (a_{A2}^{\dagger} a_{y2}^{\dagger} + a_{A2}^{\dagger} a_{y2}), $$

$$ \kappa^{(2)} = \frac{E_0^2 E_c^2 \mu_0^4 \sqrt{7N_L N_A N_c}}{576 \hbar^4 \delta' \Delta^2}. $$
Possible experimental parameters

How strong must the coupling field be?

\( \kappa^{(2)} \approx \kappa \) if

\[
\Omega_c^2 \approx \frac{48}{\sqrt{7}} \Delta \delta',
\]

where \( \Omega_c = \frac{E_c \mu_0}{\hbar} \).

How close can we go to the 2-photon resonance?

1 photon Doppler shifts almost cancel, what remains requires

\[ |\delta'| \gg \Delta_{HF} \frac{v}{c} \approx 3 \text{ kHz} \]

Taking \( \delta \approx 30 \text{ kHz}, \Delta \approx 700 \text{ MHz} \), we find \( \Omega_c \approx 10^7 \text{s}^{-1} \).

This value corresponds to the light intensity \( \sim \text{mW/cm}^2 \).
Summary of the scheme

- Multiple off-resonant Raman transitions, employing higher coherences.
- Working in parallel with the standard QND interaction: enhancing the memory capacity.
- Possibility to go close to two-photon resonance: realization of squeezer-like or of beam-splitter like transformations.
- More detailed discussion: includes two-container setup.
Single-passage read-out of atomic quantum memory

How to read the information out of the memory?

● No need of multiple passes through the medium.

● No need of feedback on the light after passing the sample.

● Price: some additional noise.

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\[ x = \frac{\kappa}{\sqrt{2}} p_A^{\text{in}} + \frac{1}{\sqrt{2}} x_L^{\text{in}} - \frac{1}{\sqrt{2}} \left(\frac{\kappa^2}{2} - 1\right) p_M^{\text{in}} - \frac{\kappa^2}{2\sqrt{6}} \tilde{p}_M^{\text{in}}, \]

\[ p = -\frac{\kappa}{\sqrt{2}} x_A^{\text{in}} - \frac{1}{\sqrt{2}} x_M^{\text{in}} - \frac{1}{\sqrt{2}} \left(\frac{\kappa^2}{2} - 1\right) p_L^{\text{in}} - \frac{\kappa^2}{2\sqrt{6}} \tilde{p}_L^{\text{in}}. \]

With coupling \( \kappa = \sqrt{2} \),

\[ x = p_A^{\text{in}} + \frac{1}{\sqrt{2}} x_L^{\text{in}} - \frac{1}{\sqrt{6}} \tilde{p}_M^{\text{in}}, \]

\[ p = -x_A^{\text{in}} - \frac{1}{\sqrt{2}} x_M^{\text{in}} - \frac{1}{\sqrt{6}} \tilde{p}_L^{\text{in}}. \]

Fidelity of coherent state reading: \( \mathcal{F} = 3/4. \)
Fidelity dependence on the absorption at the cell walls.
Summary of the scheme

- Single-passage read-out of atomic quantum memory

- No need of multiple passes through the medium or of feedback on the light after passing the sample.

- Additional noise stemming from the light mode mixing in the atomic medium.

- The fidelity is still much better than what measure-and-prepare procedures would allow.
Single-cell atomic quantum memory

- If sidebands are used, two atomic cells are needed to have QND.
- Each cell - oppositely polarized atoms.
- Can we use a single cell with two atomic polarizations?
Pumping with *linear* rather than circular polarization

T. Opatrný, arXiv quant-ph/0509094
The two processes take place in a single cell
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Problems:

● Non-equal Larmor frequencies due to nonlinear Zeeman shift.

● How to rotate the atomic quadratures?

Solutions:

● Compensate nonlinear Zeeman with ac Stark shift.

● Use imbalance between Zeeman and Stark to rotate the quadratures.

\[
\begin{align*}
\Omega_Z(m) &= \Omega_B - \frac{\Omega_B^2}{\Delta_{HF}} (2m + 1), \\
\Omega_S(m) &= \frac{\lambda^3 \gamma I_S \Delta_2}{2^8 \pi^2 \hbar c} \frac{2m + 1}{\Delta^2 - \Delta_2^2 / 4}. 
\end{align*}
\]
Summary of the scheme

- All atoms in a single cell - avoiding absorption losses, saving resources.
- Use optical pumping with linear polarization.
- Nonlinear Zeeman plays a role: use additional light and compensate Zeeman with ac Stark shift.
- Use nonlinear Zeeman and/or ac Stark to rotate quadratures.
Conclusion

- Atomic vapor: a powerful tool to build quantum memory for light.
- Use higher coherences and higher frequency sidebands to encode information.
- Overlap of different light modes to simplify reading.
- Suitable optical pumping to simplify the QND scheme.

Thank you!