Quantum Atom Optics at room temperature

Eugene Polzik
Ensemble approach

Our alternative program (1997 - ): Propagating light pulses + atomic ensembles

Energy levels with rf or microwave separation - no need for $\lambda^3$ confinement

$e^{i\delta k \cdot r} = e^{i\delta \omega \cdot r} \rightarrow 1$

Collective = ensemble quantum variables

Ground state Hf or Zeeman sublevels

Cavity QED

Strong coupling to a single atom - qubit

Caltech – optical $\lambda$

Paris – microwave

MPQ – optical

MPQ, Innsruck – ions

Stanford - solid state

...
Spin Squeezed Atoms

Very inefficient lives only nseconds, but a nice first try...
Light-Matter quantum interface

Light pulse – consisting of two modes

Strong driving

Weak quantum

Passes through one… or more atomic samples

Dipole off-resonant interaction entangles light and atoms

J. Sherson, B. Julsgaard, and E.S. P.
available on quant-ph
Examples of interfaces discussed in this talk

- Atomic entanglement
- Quantum memory

- Quasi-spin squeezing
- Clock applications

- Atomic cat state generation
- Least invasive quantum state, quantum correlations measurement
Quantum variables for light: Coherent state

\[
\begin{align*}
\left[ \hat{X}, \hat{P} \right] &= i, \\
\text{Var}(\hat{X}) &= \text{Var}(\hat{P}) = \frac{1}{2}
\end{align*}
\]

\[
\dot{E} \propto \hat{X} \cos(\omega t) + \hat{P} \sin(\omega t)
\]

Pulse:

\[
\hat{X}_L = \frac{1}{\sqrt{T}} \int_0^T (\hat{a}^+(t) + \hat{a}(t)) dt
\]
Polarization homodyning - measure $X$ (or $P$)

\[
\hat{S}_2 = \frac{1}{4} [(A + \hat{a})^+ (A + \hat{a}) - (A - \hat{a})^+ (A - \hat{a})] = \frac{1}{2} A (a^+ + a) = \frac{1}{\sqrt{2}} A \hat{X}
\]

\[
\hat{S}_3 = \frac{1}{\sqrt{2}} A \hat{P}
\]
Thermal ensemble of spin-1/2 atoms
Complimentary quantum variables for an atomic ensemble:

\[
\begin{bmatrix}
\hat{J}_z, \hat{J}_y
\end{bmatrix} = i\mathcal{J}_x \quad \delta\mathcal{J}_y \delta\mathcal{J}_z \geq \frac{1}{2} \mathcal{J}_x
\]

\[
\begin{bmatrix}
\hat{X}_A, \hat{P}_A
\end{bmatrix} = i \quad \hat{X}_A = \frac{\hat{J}_z}{\sqrt{\mathcal{J}_x}}, \quad P_A = \frac{\hat{J}_y}{\sqrt{\mathcal{J}_x}}
\]

Coherent Spin state
Object – gas of spin polarized atoms at room temperature

Optical pumping with circular polarized light

Decoherence from stray magnetic fields

Special coating – $10^4$ collisions without spin flips

Magnetic Shields
Dipole off-resonant interaction entangles light and atoms

\[ \hat{H} = a \hat{S}_3 \hat{J}_z \propto \hat{P}_L \hat{X}_A \]
Physics behind the Hamiltonian:
1. Polarization rotation of light
Physics behind the Hamiltonian:
2. Dynamic Stark shift of atoms

\[ \left| -\frac{1}{2} \right\rangle \quad \left| \frac{1}{2} \right\rangle \]

\[ \frac{1}{\sqrt{2}} (A - i\hat{\alpha}) \quad \frac{1}{\sqrt{2}} (A + i\hat{\alpha}) \]

\[ e^{i\varphi} \left| \frac{1}{2} \right\rangle \]
EPR state of two atomic clouds
2001
- **Einstein-Podolsky-Rosen paradox – entanglement; 1935**

2 particles entangled in position/momentum

\[ \hat{X}_1, \hat{P}_1 \quad \hat{X}_2, \hat{P}_2 = mV \]

\[ \hat{X}_1 - \hat{X}_2 = L \quad \hat{P}_1 + \hat{P}_2 = 0 \]

**Simon (2000); Duan, Giedke, Cirac, Zoller (2000)**

Necessary and sufficient condition for entanglement

\[ \delta (X_1 - X_2)^2 + \delta (P_1 + P_2)^2 < 2 \]
Experimental long-lived entanglement of two macroscopic objects.


- 10¹² spins in each ensemble
- Spins which are “more parallel” than that are entangled
Stern-Gerlach projection on any axis $\perp$ to $x$:

Along $y,z$: **ideally no** misbalance between heads and tails of the two ensembles, or, at least, less than random misbalance $\sqrt{N}$.
Material objects deterministically entangled at 0.5 m distance

Quantum uncertainty

\[ \sqrt{2J_x} \]

\[ J_{z1} + J_{z2} \quad \text{or} \quad J_{y1} + J_{y2} \]

Niels Bohr Institute
December 2003
Quantum Memory for Light
2004
What do we want to achieve?

Quantum memory for light

Classical approach - measure and write

Problem:
Cannot measure an unknown state

Example:
single polarized photon
Preparation of the input state of light

Strong field $A(t)$

Polarizing cube

Quantum field - X,P

EOM

$X$

$\hat{P}$

$\hat{X}$

Vacuum Coherent Squeezed

Input quantum field

Polarization state
Implementation: light-to-matter state transfer

No prior entanglement necessary

\[ \hat{H} = a \hat{S} \hat{J}_z \propto \hat{P}_L \hat{X}_A \]

\[ \hat{P}_A^{\text{mem}} = \hat{X}_A^{\text{in}} + \hat{P}_L^{\text{in}} \]

\[ \hat{X}_L^{\text{out}} = \hat{X}_L^{\text{in}} + \hat{X}_A^{\text{in}} = C \]

\[ \hat{X}_A^{\text{mem}} = \hat{X}_A^{\text{in}} - C = -\hat{X}_L^{\text{in}} \]

squeeze atoms first

F \rightarrow 100\%

F \approx 80\%

B. Julsgaard, J. Sherson, J. Fiurášek, I. Cirac, and E. S. Polzik
Readout pulse

Detectors

PC

Integrator

EOM

RF-feedback

Optical pump

Feedback

1ms

τ

π/2-rotation

Pulse sequence

Local oscillator

Lockin amplifier

Integrator

Verdi V8

Pulse shape

ti:sapph

S_x/S_y-modulation

Local oscillator

Lockin amplifier

Integrator

Input pulse

Magnetic feedback

Quantum tomography of the collective atomic state
Stored state versus Input state: mean amplitudes

Gain plot for $S_y$ and $S_z$ modulation.

- $g_F = 0.797$
- $g_{BA} = 0.836$

Atomic mean value [xp-units]

Mean($S_y$ or $S_z$) [xp-units]

$y = 0.797 \times x$

$y = 0.836 \times x$

$P_{in} \sim S_{Yin}$

$X_{in} \sim S_{Zin}$

Magnetic feedback

Read

Write

X plane

Y plane

$\pi/2$ rotation

Read write

$t$
Stored state: variances

\[ \langle P_{\text{mem}}^2 \rangle > \]
\[ \langle X_{\text{mem}}^2 \rangle > \]

\[ \langle P_{\text{in}}^2 \rangle = 1/2 \]
\[ \langle X_{\text{in}}^2 \rangle = 1/2 \]

Absolute quantum/classical border

\[ 1+2g^2 = 2.31 \text{ (classically best for } n \leq 8) \]

\[ \sigma_{BA}^2 = 1.818(75) \times PN \]
\[ \sigma_F^2 = 1.643(67) \times PN \]

PN level

Perfect mapping
Fidelity of quantum storage

\[ F = \int P(\Psi_{in}) \langle \Psi_{in} | \hat{\rho}_{out} | \Psi_{in} \rangle d | \Psi_{in} \rangle \] - State overlap averaged over the set of input states

Experiment

Coherent states with \(0 < n < 8\)

Best classical mapping

Gain

Coherent states with \(0 < n < 4\)

Best classical mapping
Quantum memory lifetime

Fidelity versus delay. Calculated for $<n> \leq 10$.

Fidelity [%]

Pulse delay [ms]

- Quiet data
- Extrapolated

Classical limit

16-06-2004/mapping.opj
Single photon state source for atomic memories
2006
Photon subtracted squeezed vacuum

Squeezed cavity mode

Squeezed state:

\[ |\psi\rangle = \frac{1}{\cosh \zeta} \sum_{n=0} (\tanh \zeta)^n |2n\rangle \approx |0\rangle + \zeta |2\rangle + O(\zeta^2) \]

After photon subtraction

\[ |1\rangle \]
Quantum interface with cold atoms

**CESIUM LEVEL SCHEME**

<table>
<thead>
<tr>
<th>Level</th>
<th>Frequency</th>
<th>F Value</th>
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</thead>
<tbody>
<tr>
<td>6P(^{3/2})</td>
<td>251 MHz</td>
<td>F=5</td>
</tr>
<tr>
<td>201 MHz</td>
<td>F=4</td>
<td></td>
</tr>
<tr>
<td>152 MHz</td>
<td>F=3</td>
<td></td>
</tr>
<tr>
<td>6P(^{1/2})</td>
<td>1.17 GHz</td>
<td>F=4</td>
</tr>
<tr>
<td>852 nm</td>
<td>F=3</td>
<td></td>
</tr>
<tr>
<td>6S(^{1/2})</td>
<td>9.192 GHz</td>
<td>2</td>
</tr>
<tr>
<td>F=4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
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</tbody>
</table>

\[ J_x = \frac{N_a}{L} \int_0^L (\sigma_{12} + \sigma_{21}^+)dz \]

\[ J_y = \frac{N_a}{L} \int_0^L (\sigma_{12} - \sigma_{21}^+)dz \]

\[ J_z = \frac{N_a}{L} \int_0^L (\sigma_{11} - \sigma_{22})dz \]
Spin squeezing with cold atoms (clock transition in Cs)
Interferometry on a pencil-shaped atomic sample - 2005 (dipole trap)
Quantum noise limited sensitivity to number of atoms

Spin noise, $(\delta \phi)^2$ [Rad x 10^{-4}]

Dc-Phase shift, $\phi_\Delta$ $\otimes$ $N_{at}$ [Rad]
Non-destructive measurement of Clock oscillation

phase-shift w u-wave b.g. subtracted, [V]

probe pulse rep. period 160us
(approx. half Rabi-period)

low probe power