Storing and manipulating quantum information using atomic ensembles

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Plan:

- Basic concepts and ideas
  - Application of quantum optics techniques
  - Some mathematics
  - Relation of cavity QED & collective enhancement
- Examples of current research:
  - Quantum state manipulation of atoms and photons via Raman scattering & photo-detection
  - Towards enhanced nonlinear optics with stationary pulses of light in atomic medium
  - Application in condensed matter: nuclear spin ensembles in quantum dots
Quantum coherence: linear vs nonlinear systems

- Most non-trivial task in quantum information processing:
  - Coherent manipulation of coupled, interacting, non-linear (unharmonic) systems, e.g. qubits

- Harmonic (linear) systems are often used:
  - to mediate interactions between qubits
  - to store quantum states of qubits

- Examples: cavity QED (two level atom + one mode of radiation)
  - ion trap (ion spin + mode of center of mass motion)
  - superconductors (Cooper pair box + mode of voltage)

- Note:
  (large) nonlinearity or quantum measurement is required to make the system behave quantum mechanically
This talk

- new tools for coherent localization, storage and processing of light signals

- Specifically quantum networks & quantum communication …

… need new tools:
- photons for communication, matter for storage
- interface for reversible quantum state exchange between light and matter
- compatible methods to produce, manipulate …non-classical states
Ongoing efforts

• Use single atoms for memory and absorb or emit a photon in a controlled way
  Cirac, Zoller, Mabuchi, Kimble, PRL 78, 3221 (1997)

✓ Problem: single atom absorption cross-section is tiny ($\sim \lambda^2$)
✓ Cavity QED: fascinating (but also very difficult) experiments

  S. Haroche (ENS)
  H. Walther (MPQ)
  J. Kimble (Caltech)
  G. Rempe (MPQ)
  Y. Yamamoto (Stanford)

+ new ideas: cavity QED on a chip

• Photons interact strongly with large ensembles of atoms

… but usual absorption does not preserve coherence
✓ Main challenge: coherent control of resonant optical properties
  • “force” the atoms behave the way we want!
Electromagnetically Induced Transparency

- coherently controlled, optically dense medium
- control field \((\Omega)\)
- signal field
- spin coherence causes destructive interference in absorption
- the stronger the group velocity \(v_g\), the slower the light

Early work: Alzetta, Arimondo, Eberly, Bergman, Harris, Kocharovskaya, Mandel, Scully, Imamoglu
Coupled propagation of photonic and spin wave: “dark state polaritons”

\[ \hat{\Psi} = \cos \theta \hat{a} - \sin \theta \hat{S}_- \]

\[ \cos^2 \theta = \frac{v_g}{c} = \frac{\Omega^2}{\Omega^2 + g^2 N} \]

✓ Strongly coupled excitations of light and spin wave slowly propagate together … and can be manipulated
Dark states for quantum fields: a toy model

- One atom interacting with one mode of quantum field + one classical field

\[ H = g a | \downarrow \rangle \langle e | + | \uparrow \rangle \langle e | \Omega + h.c. \]

- Consider \( | \Omega \rangle = | \downarrow \rangle | n = 0 \rangle \) not affected: \( H | \downarrow \rangle | 0 \rangle = 0 \)

- The idea: adiabatic change of \( \Omega \) allows to reversibly convert photon state into atomic spin state, i.e. map photonic into atomic qubits

\[ \Psi = \cos \theta a - \sin \theta | \downarrow \rangle \langle \uparrow | \]

\[ [H, \Psi] = 0, \text{ if } \tan \theta = \frac{\Omega}{g} \]

- \( \Psi^\dagger \) creates dark state: \( H \Psi^\dagger | g \rangle = 0 \)

(early work P. Zoller et al 93-97)
Conditions for coherent dynamics

- Implementation of one atom + one mode system: cavity QED

- Two decay channels:
  \[ H_{eff} = ga |\downarrow\rangle \langle e| + |\uparrow\rangle \langle e| \Omega + h.c. \]
  \[ + \frac{i}{2} \gamma |e\rangle \langle e| + \frac{i}{2} \kappa a^+ a \]

- Jump probability:
  \[ p \sim \int_0^T [\gamma \rho_{ee}(\tau) + \kappa \rho_{11}(\tau)] d\tau \]

- Depend on passage time \( T \):
  \[ p \sim \frac{\gamma}{g^2 T} + \kappa T \rightarrow \sqrt{\frac{\gamma \kappa}{g^2}} \]

Physics (Purcell condition):
\[ \frac{g^2}{\kappa \gamma} \sim \frac{\lambda^2}{A} \times F \gg 1 \]

beam area \quad cavity fineness
Dark states for quantum fields: system of N atoms

✓ N atoms interacting with one mode of quantum field + one classical field

\[ H = g a \sum_{i=1}^{N} | \downarrow_i \rangle \langle e | + \sum_{i=1}^{N} | \uparrow_i \rangle \langle e | \Omega + h.c. \]

\[ |g\rangle = | \downarrow_1 \ldots \downarrow_N \rangle |n = 0\rangle \]

\[ \Psi = \cos \theta \ a - \sin \theta \ S, \text{ where } S = \frac{1}{\sqrt{N}} \sum | \downarrow_i \rangle \langle \uparrow_i | \]

\[ [H, \Psi] = 0, \text{ if } \tan \theta = \frac{\Omega}{g\sqrt{N}} \]

• Create family of dark states \[ H (\Psi^+)^n |g\rangle = 0 \]

✓ couple to collective spin states \[ (S^+)^n |g\rangle \]

✓ coupling strength enhanced \[ g \rightarrow g\sqrt{N} \]

✓ for low n<<N, correspond to bosonic excitations\[ [S, S^+] \approx 1 \]
Bottom line: photons interacting with N-atom system

- Coherent rate of interactions enhanced (collective enhancement):
  \[ \frac{g^2 N}{\gamma \kappa} \sim \frac{L}{L_{abs}} \gg 1 \]

- Light now couples to collective excitations which have harmonic spectrum

- N.B. Extension to multimode case straightforward

\[ S_k = \sum_i |\downarrow\rangle_i \langle\uparrow| \exp(ikz_i), \quad \Psi_k = \cos\theta a_k - \sin\theta S_k \]

\[ \left[ \cos^2\theta \frac{\partial}{\partial z} + \frac{\partial}{\partial t} \right] \Psi = 0 \]
“Photon trap”: coherent quantum state transfer between light and atoms

- Adiabatic passage in coupled excitations ("dark-state polaritons")

- Light wave is coherently converted into a spin wave i.e. absorbed in a coherent way!
- Storage time is limited by spin coherence lifetime
- Retrieval by turning on control field

- Linear optical technique: no change in quantum statistics (ideally)
- No light is present after the pulse is stopped

Theory: Fleischhauer, Yelin, Lukin
PRL, 84, 4232 (2000),
PRL, 84, 5094 (2000)

Expts (weak classical pulses):
Liu et al, Nature 409, 490 (2001)
Phillips et al, PRL 86 783 (2001)

undergrad physics lab:
PHYS 191 @ http://physics.harvard.edu
Quantum control of light and atomic ensembles

- **Need:** techniques for creating & manipulating quantum states of photons or spin waves at a level of single quanta

**Two approaches**

- **✓ Use weak nonlinearity** and quantum measurement

- **Atom and photonic state preparation** via Raman scattering
  
  (weak nonlinearity and quantum measurement)

- **Create large nonlinearity** at a level of single atoms or photons

- Developed using dipole-dipole interactions of Rydberg states
  
  *Stationary pulses of light in atomic medium
  
  towards enhanced nonlinear optics via second order
Manipulating quantum states via Raman scattering & quantum measurements
Atom-photon correlations in Raman scattering

- Absorption of pump photon produces a pair of flipped spin and Stokes photon

- Flipped spins and Stokes photons are strongly correlated:
  when $n$ Stokes photons emitted $n$ spins are flipped

- Spontaneous Stokes photons have arbitrary direction

- ...but each emitted photon is uniquely correlated with a well defined spin-wave mode due to momentum conservation

$$\hbar k_{Pump} = \hbar k_{Stokes} + \hbar k_{Spin}$$

Blombergen, Raymer
Raman preparation of atomic ensemble

• Raman process produces pairs of spins flips and photons:

\[ H = \frac{g\sqrt{N}\Omega_w}{\Delta} a_k^+ S_k^+ + h.c. \]

• Stokes field and spin wave undergo mutual growth and become entangled:

\[ \text{state} \sim |g\rangle + \lambda |\uparrow^1\rangle |n_s = 1\rangle + \lambda^2 |\uparrow^2\rangle |n_s = 2\rangle + \ldots \]

• Quantum measurement can be used to prepares the state of atomic ensemble: detecting \( n \) Stokes photons in certain mode “projects” atomic state with exactly \( n \) excitations in a well-defined mode
Retrieving the state of spin wave

- Stored state can be converted to polariton and then to anti-Stokes photon by applying resonant retrieve control beam.

- Retrieval beam prevents re-absorption due to EIT, controls propagation properties of the retrieved (anti-Stokes) pulse.

✓ Source of quantum-mechanically Stokes and anti-Stokes photons analogous to “twin beams” in parametric downconverters but with build-in atomic memory!

Duan et al, Nature 414, 413 (2001)
Andre, Duan, MDL, PRL 88 243602 (2002)
Single atoms vs atomic ensembles

• Single atom case

- anti-Stokes
- write control
- retrieve control
- Stokes

• In atomic ensemble:

✓ we don't know which particular spin flips: collective states are excited
✓ collective states store all quantum correlations, allow for readout via polaritons, directionality, pulse shaping as long as spin coherence is preserved!
Applications of Raman quantum state manipulation

- Shaped single photon and number-squeezed light source: detecting $n$ photons in a certain mode of Stokes light selects a spin-wave mode and "projects" its state to a Fock state.

- Stored state can be converted to anti-Stokes photons with defined timing, direction
  first experimental results: see L.Childress poster

- Instead of detection Stokes photon can be converted into flipped spins:
  controlled atom interactions
  Andre, Duan, Lukin, PRL 88 243602 (2002)

- Long distance quantum communication in lossy channels:
  "quantum repeater" techniques
  Duan, Lukin, Cirac and Zoller, Nature 414, 413 (2001)
Entanglement generation between atomic ensembles via Raman scattering and photodetection

- Simultaneous Raman scattering from two ensembles

![Diagram of Raman scattering](image)

- After interference at BS it is impossible to determine where Stokes photon came from: results in an entangled state of two ensembles

\[
|\Psi\rangle_{LR} \sim e^{-L/L_{abs}} |g\rangle_L |1_+\rangle_R + e^{-L/L_{abs}} |1_+\rangle_L |g\rangle_R
\]

(an example of "probabilistic" entanglement)

- Remarkably the same state will be created even in the presence of photon losses, provided those are equal in different arms
Application: quantum communication over long distances

- Technique can be cascaded over multiple nodes to correct common errors with only Raman scattering, storage & retrieval and linear optics

- Bottom line: "quantum repeater" for long-distance entanglement generation

![Diagram of quantum repeater](chart)

* efficiency of storage + detection ~ 50 % is assumed

Duan, Lukin, Cirac and Zoller, Nature 414, 413 (2001)

✔ Can allow quantum cryptography, teleportation … over long distances

See also B.Blinov et al, Nature, in press
Experimental progress: shaping quantum pulses of light via atomic memory

Goal: generate (anti-Stokes) pulses of light with well-defined number of photons, timing, shapes, direction

- medium: N~10^{10} Rb atoms + buffer gas, hyperfine states for storage, Raman frequency difference 6.8 GHz
- implementation: long-lived memory allows to make pulses long compared to time resolution of single photon counters

Early work: C. van der Wal et al., Science, 301, 196 (2003)
Example: (classical) correlations in Raman preparation & retrieval

\[ \tau_d = 200 \text{ ns} \]

Stokes
Anti-Stokes (x5)
Non-classical correlations in preparation and retrieval

\[ V = \frac{\text{variance of difference}}{\text{photon shot noise}} \]

\(< 1 \quad \text{nonclassical} \]

\(= 0 \quad \text{ideal correlations} \]

\(V = 0.95 \pm 0.01\)

• Vary the delay time between preparation and retrieval

\(\checkmark\) V > 0 due to imperfections (loss and background)

✓ Nonclassical correlations exist within spin coherence time
Example of quantum control: shaping few-photon pulses

- Idea: rate of retrieval (polariton velocity) is proportional to control intensity

✓ Duration, shape of retrieved pulses controllable
Conditional preparation of non-classical pulses

\[ g^{(2)}(\text{AS}) = \frac{\langle \text{AS}_1 \cdot \text{AS}_2 \rangle}{\langle \text{AS}_1 \rangle \langle \text{AS}_2 \rangle} \]

- \( \geq 1 \) classical
- \(< 1 \) quantum
- \( = 1 - 1/n \) Fock state

✓ Conditional generation of few-photon light pulses with suppressed intensity fluctuations; current limitations: losses and background

M. Eisaman, L. Childress, F. Massou, A. Andre, A. Zibrov, MDL
Summary of Raman state manipulation

✓ Probabilistic technique to prepare quantum states of matter & light
✓ First experimental results
✓ Can be used for long-distance quantum communication
Quantum control of light and atomic ensembles

- Need: techniques for creating & manipulating quantum states of photons or spin waves at a level of single quanta

Two approaches

- Use weak nonlinearity and quantum measurement
  - Atomic and photonic state preparation via Raman scattering (weak nonlinearity and quantum measurement)
  - Use small number of single quanta or spin waves at a level of single quanta

- Create large nonlinearity at a level of single atoms or photons
  - Dipole blockade: strong dipole-dipole interaction of (Rydberg) atoms
  - Stationary pulses of light in atomic medium: towards enhanced nonlinear optics with stored states
Stationary light pulses in an atomic medium: toward enhanced nonlinear optics

- Key idea: controlled conversion of the propagating pulse into the excitation with localized, stationary electromagnetic energy

- Mechanism: Bragg reflections from controlled, spatial modulation of the atomic absorption

- New possibilities for enhanced nonlinear optical processes, analogous to cavity QED
EIT in a standing wave control light

Optical properties of EIT medium …

… are modified by standing-wave control field:
produces sharp modulation of atomic absorption in space

Such medium becomes high-quality Bragg reflector
500 kHz signal frequency transmission (running wave)
transmission (standing wave)
reflection (standing wave)

EIT spectra: running vs. standing wave control

Theory:

signal amplitude (arb. units)

signal frequency detuning

PD2
medium
PD1

FD
BD
Idea of this work

✓ Releasing stored spin wave into modulated EIT medium creates light pulse that cannot propagate
Propagation dynamics: storage in spin states

control light

signal light

spin coherence
Propagation dynamics: release in standing wave

control light

signal light

spin coherence
Stationary pulses of light bound to atomic coherence

Physics:
- analogous to "defect" in periodic (photonic) crystal:
  - finess ($\mathcal{F}$) of localized mode determined by optical depth
- Localization, holding, release completely controlled
- In optimal case, no losses, no added noise, linear optical technique

Observing stationary pulses of light

 Released pulse amplitude

 forward signal

 time

 FD

 BD

 PD1

 PD2

 Rb cell

 FD

 BD

 signal amplitude (arb. units)

 10 µs

 Backward pulse duration ($t_B$) vs. Released pulse amplitude

 Released pulse amplitude

 0.8

 0.4

 0.0

 0

 5

 10

 15

 20

 25

 30

 Backward pulse duration ($t_B$) [µs]
Proof of stationary pulses

• measure fluorescence caused by the stationary light pulse

M.Bajcsy, A.Zibrov & MDL
Outlook: novel techniques for nonlinear optics

✓ Efficient nonlinear optics as a sequence of 3 linear operations

✓ Nonlinear shift results from interaction of photonic components of stationary pulse with stored spin wave

\[ \phi_{NLN} \sim \frac{\lambda^2}{A} n_{photon} \times \mathcal{F} \]

✓ Nonlinear processes at a few-photon level are realistic
Example from condensed matter:
controlling mesoscopic environment in solid state

• Short coherence time: limiting factor for solid-state quantum control
e.g. for electron spins in GaAs dots \( \sim \) fraction of \( \mu s \)
  ✓ Reasons: … interaction with surrounding ensemble of nuclear spins
  ✓ Idea: use long nuclear memory to suppress decoherence and
    store the states of qubits
Idea of quantum memory: storing electron spin in collective nuclear spin states

- Controlled coupling of electronic and nuclear spins
  - contact hyperfine interaction, spin-polarized nuclei
  - control tool: effective magnetic field
  - allows for resonant spin-exchange and quantum state transfer

\[
\hat{H} = (\hbar g \mu_B B_0 - \sum A_i/2)\hat{S}_z + \sum A_i (\hat{I}_+ \hat{S}_- + \hat{I}_- \hat{S}_+) \\
\text{Zeeman+Overhauser} \quad \text{Spin Exchange}
\]

- Inverting the procedure maps the state back into the electron qubit

✓ In many way analogous to single atom + radiation field
Spin qubit storage in collective nuclear states

\[ \left( \alpha |\uparrow\rangle + \beta |\downarrow\rangle \right) \otimes |\uparrow .. \uparrow\rangle_N \xrightarrow{\Omega} |\uparrow\rangle \otimes \left( \alpha |\uparrow .. \uparrow\rangle + \beta \sum_i A_i |\uparrow .. \downarrow_i .. \uparrow\rangle / \Omega_R \right)_N \]

- Time scale for collective state transfer (GaAs, \( \sim 10^5 \) nuclei)
  - hyperfine coupling per nuclear spin \( \sim 0.1 \) GHz: fast!
- Dephasing mechanisms during storage
  - Inhomogeneous hyperfine coupling \( \sim \) fraction of MHz
    - Can be canceled by ESR of NMR pulse sequences
  - Nuclear dipole-dipole diffusion & dephasing \( \sim 4 \) KHz
    - Standard NMR pulse trains to cancel leading order

✓ Coherent storage times \( \sim \) seconds possible

Taylor, Marcus & Lukin

✓ Can be accomplished with low nuclear polarization

Quantum manipulation of nuclear ensembles

Based on spin degrees of freedom ONLY

• Single electron spin used to carry quantum information

• Local interactions between nuclear ensembles and electron spin (unharmonic system) are sufficient for entanglement

electron spin: transport

nuclei: memory

✓ New techniques for quantum computation and quantum communication in solid state

J. Taylor, A. Imamoglu, P. Zoller & MDL
Summary

• Quantum memory for light (photon state trapping) via EIT

• Raman scattering for preparation of non-classical states of atoms and light
  shaping quantum pulses via Raman scattering & EIT
  new techniques for long distance quantum communication

• Stationary pulses of light in atomic medium
  proof of principle experiments
  new nonlinear optical techniques

• Quantum state manipulation in solid state
  long-lived memory for spins in q.dots
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