Update on Walsworth/Lukin "stored light" collaboration at Harvard

- Context: who, what, where, when…
- Review of first stored light demos in vapor cells:
  - *classical light pulses*
  - *phase coherence and control*
- Planned experiments to test theory & optimize technique
- Outline of plan to demonstrate single-quantum storage
- Recent measurements of statistics of Raman light
- Maybe a brief word about our CPT clock work
- Some recommended theory papers

Context

Two groups:

Ron Walsworth, PI
Harvard-Smithsonian Center for Astrophysics (CfA)
Experimental atomic physics
- *Atomic clocks*
- *Symmetry tests*
- *Soft matter and biophysics with NMR*
- *"Stored light" and related topics*

Mikhail Lukin, PI
Harvard University Department of Physics
Theoretical physics + a little experiment
- *Quantum optics ("stored light" et al.)*
- *Quantum information*
- *Applications to condensed matter*

Context

People:

Ron Walsworth, Smithsonian Federal scientist, adjunct Harvard faculty
Mikhail Lukin, Harvard Asst. Professor
David Phillips, Smithsonian staff scientist
A. Zibrov, senior Smithsonian visiting scientist
Caspar van der Wal, postdoc

Axel Andre
Michal Bajcsy
Jean Hager
Michael Hohensee
Ludwig Matthey
Brian Murphy
Jake Taylor

graduate students

Annet Fleischhauer
Alois Mair

former members

Context

Timeline:

Essential "stored light" theory by Fleischhauer, Lukin & Yelin	1999 – 2000
Idea for stored light experiments at CfA	early 2000
First warm & cold atom experiments	late 2000
Phase coherence/control demo	early 2001
CfA lab returns to clock work, new lab built at Harvard Physics	late 2001
Work toward single-quantum storage	2002 –>
New CfA lab to be built for stored light and related projects	late 2002

Phase velocity: $v_p = \frac{\omega(k)}{k} = \frac{c}{n(k)}$

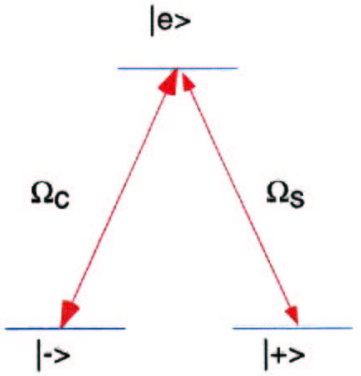
Group velocity:

$$v_g = \frac{d\omega}{dk} = \frac{c}{n(\omega)+\omega(dn/d\omega)}$$

$\Rightarrow$ slow group velocity near steep positive variation of refractive index with frequency

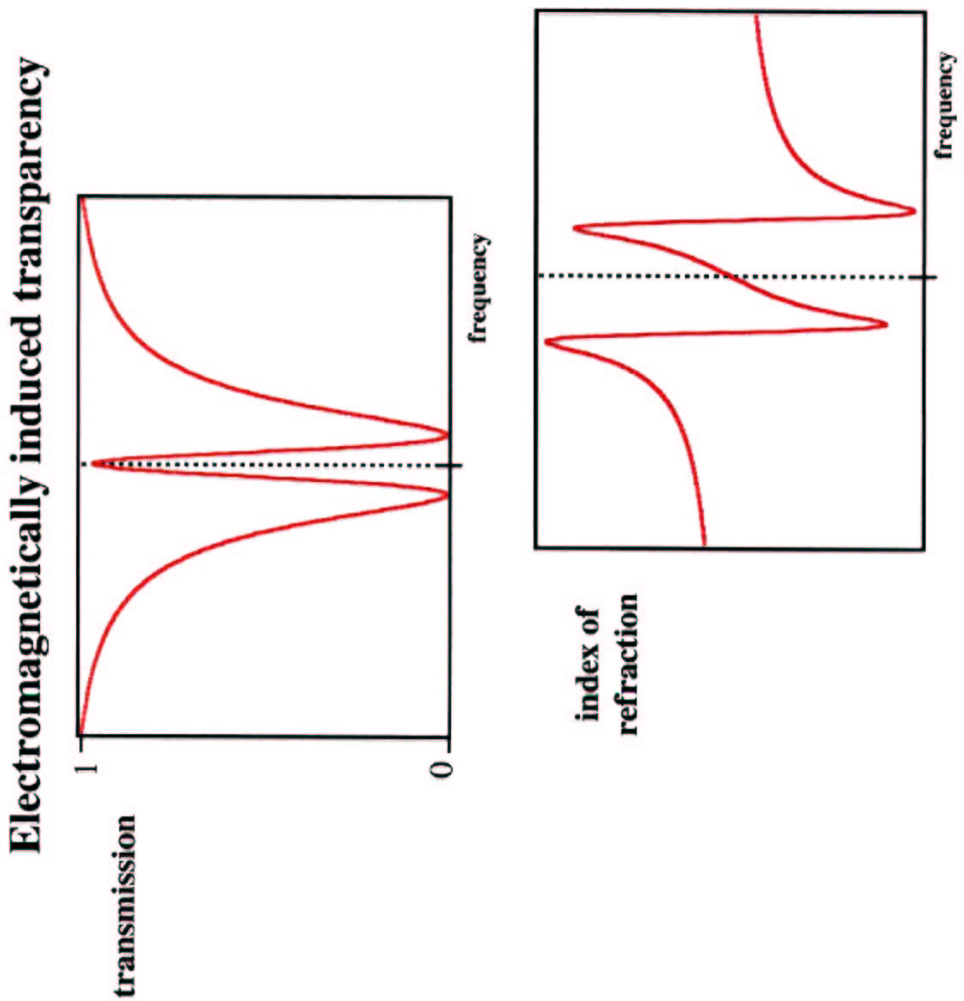
$\Rightarrow$ $v_g \longrightarrow 0$ when $\frac{dn}{d\omega} \longrightarrow \infty$

Electromagnetically Induced Transparency



- Interference between absorption paths
- With atoms in appropriate state, no absorption

$$|dark\rangle = \frac{\Omega_c |+\rangle - \Omega_s |-\rangle}{\sqrt{|\Omega_c|^2 + |\Omega_s|^2}}$$



Advantages of EIT

- Controllable dispersion relation
  ⇒ easy manipulation of group velocity, transparency window, pulse compression, etc.

  can make $\frac{dn}{d\omega} \longrightarrow \infty \Rightarrow v_g \longrightarrow 0$

- Strong interaction of atoms and light on 2-photon Raman transition with no 1-photon absorption
  ⇒ efficient information transfer

- Long coherence times of ground states
  ⇒ long-lived information storage

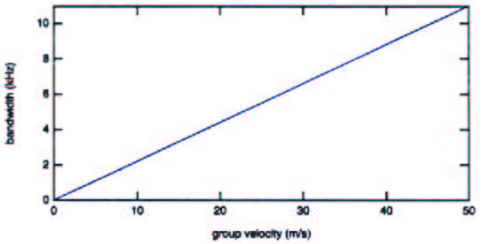
EIT Transparency Window

Group velocity drops with laser power:

$$V_g = \frac{\Omega_c^2}{2\gamma N\sigma}$$

Bandwidth of transparency also drops:

$$\Delta\nu_{\max} < \frac{\Omega_c^2}{2\gamma\sqrt{N\sigma L}}$$



Harris and Hau, PRL, **82** *4611 (1999).*

Problem: use EIT to make $v_g = 0$

Using "conventional" slow light technique:
Set control beam to low power
⇒ v_g reduced AND transparency window is narrowed
⇒ pulse length goes to infinity in limit that v_g goes to zero, otherwise pulse is absorbed.

Solution: use dynamic EIT

1) Set control beam to moderate power
⇒ both v_g and transparency window have moderate values
⇒ reasonable length pulse enters medium and slows down
spatial compression of pulse by ~ 10^5
no change to temporal extent of pulse

2) Reduce control beam to zero
⇒ v_g, transparency window, AND spectral bandwidth of pulse go to zero
⇒ pulse halted with no absorbtion
infinite temporal expansion of pulse
no change to spatial profile

Dark-State Polaritons

Dark-Sate Polaritons, Ψ, are a linear combination of atomic (ρ) and photonic (Ω_s) excitations.

$$\Psi(z,t) = \cos\theta\Omega_s(z,t) - \sin\theta\sqrt{\kappa}\rho_{-+}(z,t)$$

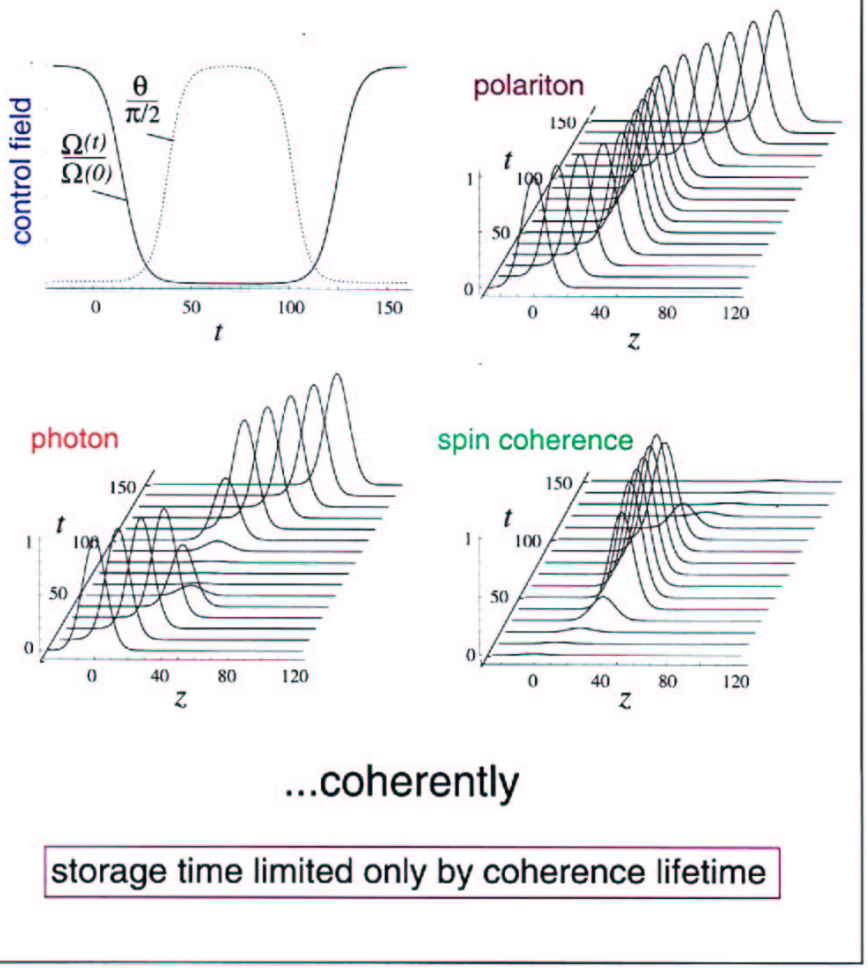
$$\tan\theta = \frac{\sqrt{\kappa}}{\Omega_c}$$

$$\frac{v_g}{c} = \cos^2\theta = \frac{\Omega_c^2}{\Omega_c^2 + \kappa}$$

The polariton shape is preserved as the light intensity (parameterized by θ) is varied adiabatically.

Fleischhauer and Lukin, PRL, **84** *5094 (2000).*

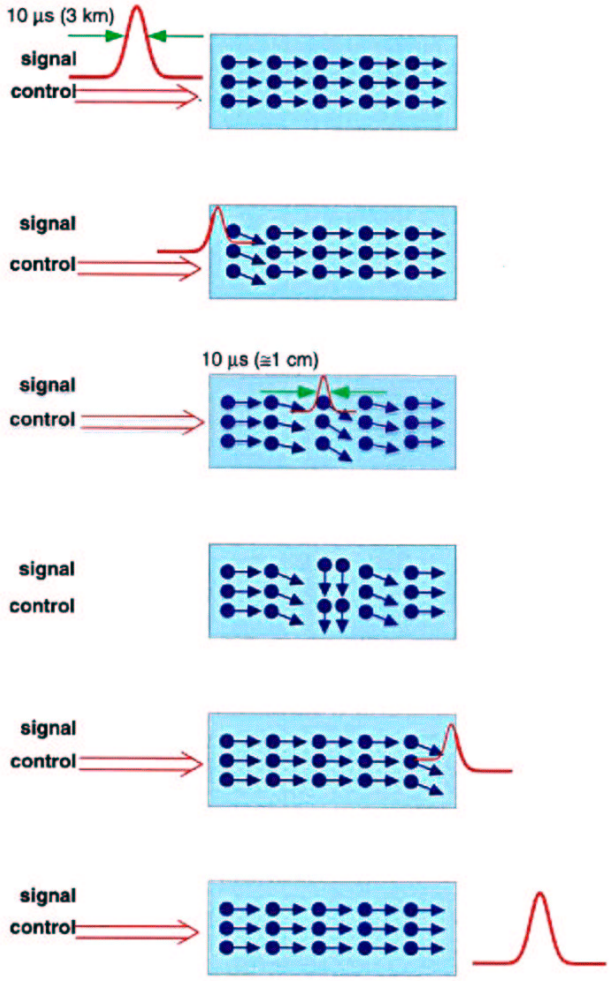
How to store photons...



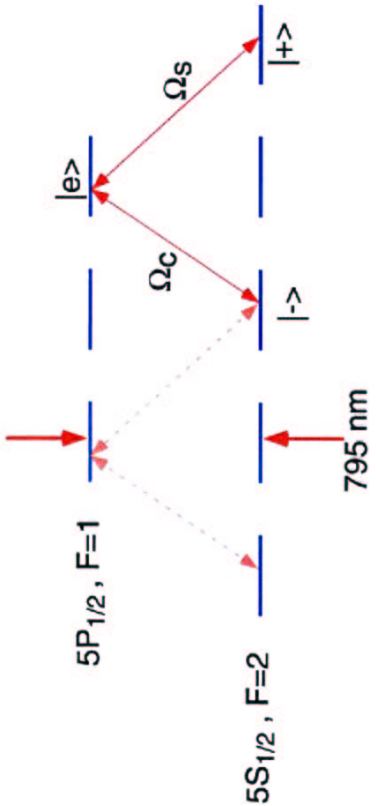
...coherently

storage time limited only by coherence lifetime

Light Storage

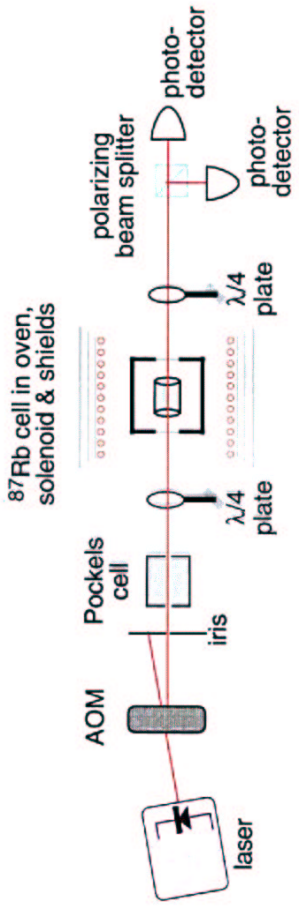


Rb Levels used for Stored Light



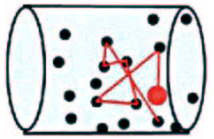
- Control field initially optically pumps atoms to $|+\rangle$ state.
- Most of the population remains in $|+\rangle$.
- $|-\rangle$ stores the pulse information.
- Additional coherence in left-most state.

Experimental Apparatus



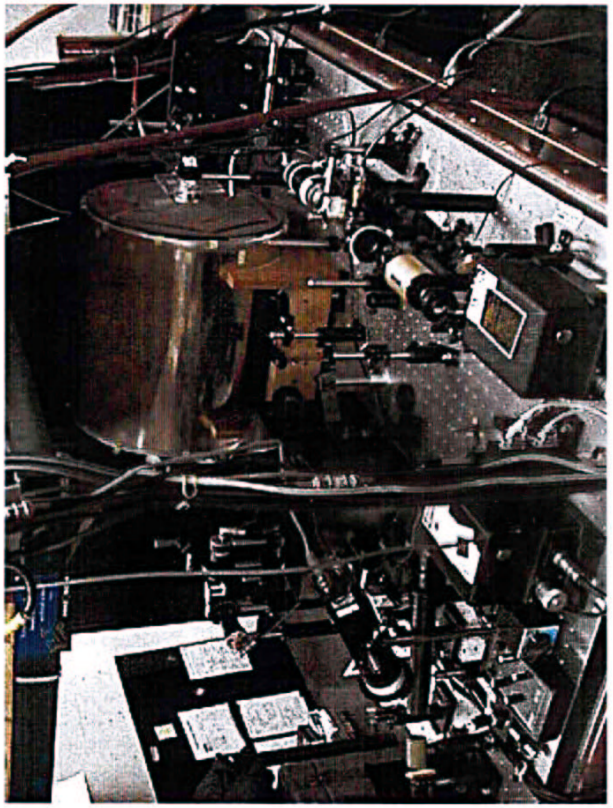
- Acousto-optic modulator adjusts intensity of control field.
- Pockels cell rotates the polarization to produce the pulse.
- $\lambda/4$ plates convert linear polarizations to circular (σ_+ and σ_-) and back.
- ^{87}Rb atoms in buffer gas cell, blown air oven, solenoid and magnetic shields.
- A polarizing beam splitter and two photodetectors allow for polarization analysis.

Vapor Cell

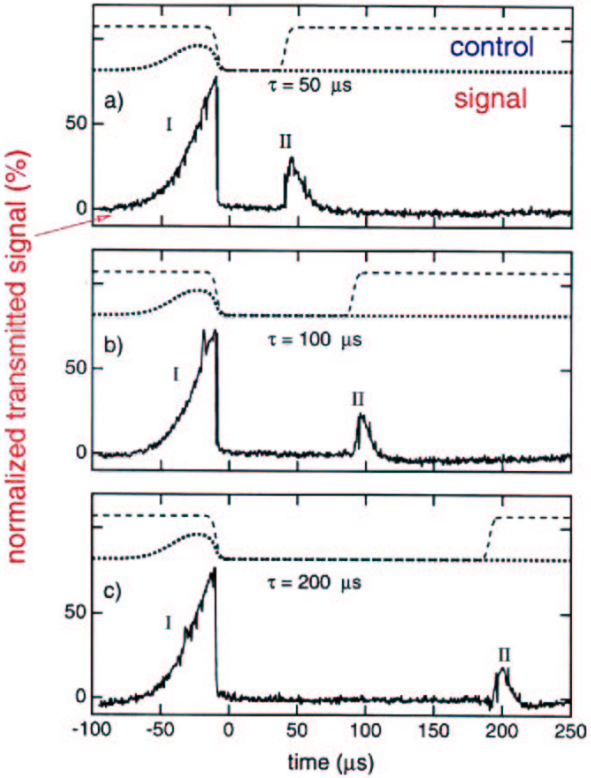


- Warm vapor of Rb (T $\approx 80°$C)
- He buffer gas (P = 5 Torr)
- *A 1 mm beam diameter* $\rightarrow 100\mu s$ *storage times.*
- Buffer gas densities of up to 100 Torr have been used in Rb masers while maintaining long coherence times ($T_2 > 10$ ms).
  (J. Vanier, Phys. Rev., **168** *129 (1968).)*

Stored Light Apparatus



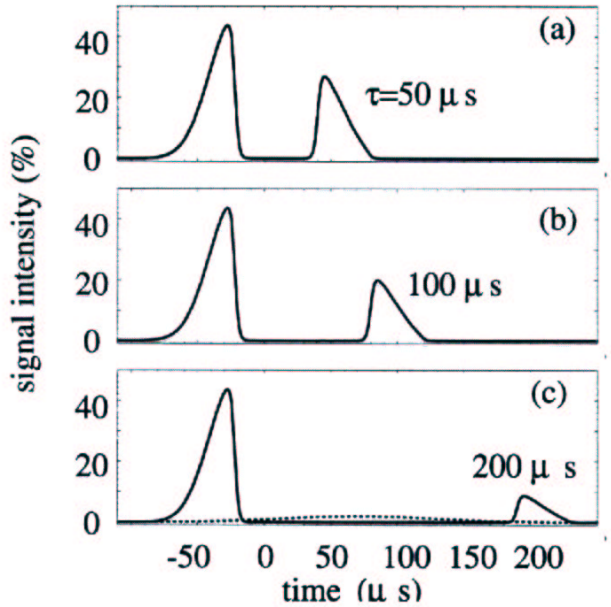
"Storage of light": data



- up to 50% of input pulse is "stored"
- storage intervals up to ~ 0.5 ms are observed

Phillips, Fleischhauer, Mair, Walsworth, Lukin, PRL 86,783 (2001)
(see also Liu, Hau, et al., Nature 409, 490 (2001))

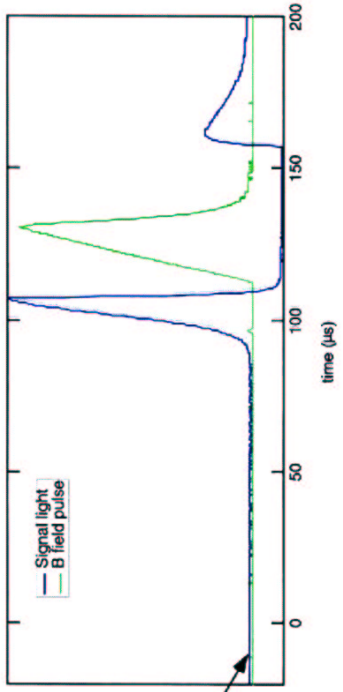
Calculations



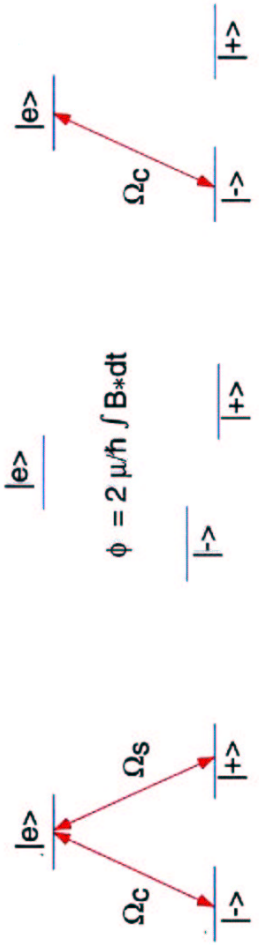
Calculations match well to observed pulse heights with time constant of $\sim 150\mu s$.

Writing a Phase on Stored Light

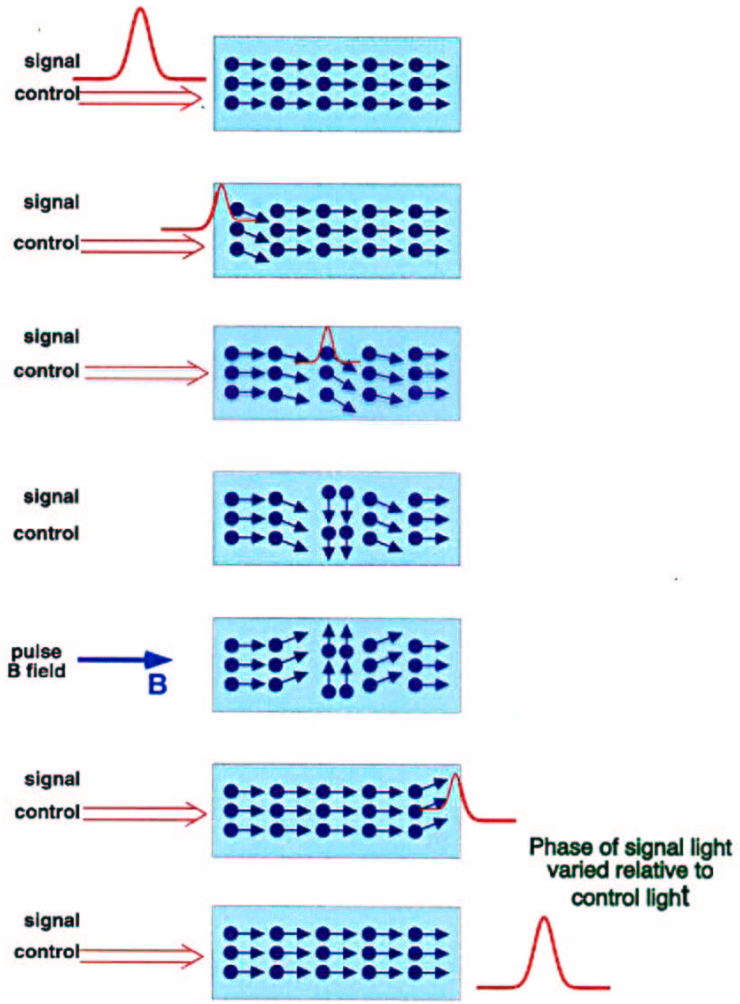
Apply a pulsed magnetic field —> vary phase of stored light relative to control light



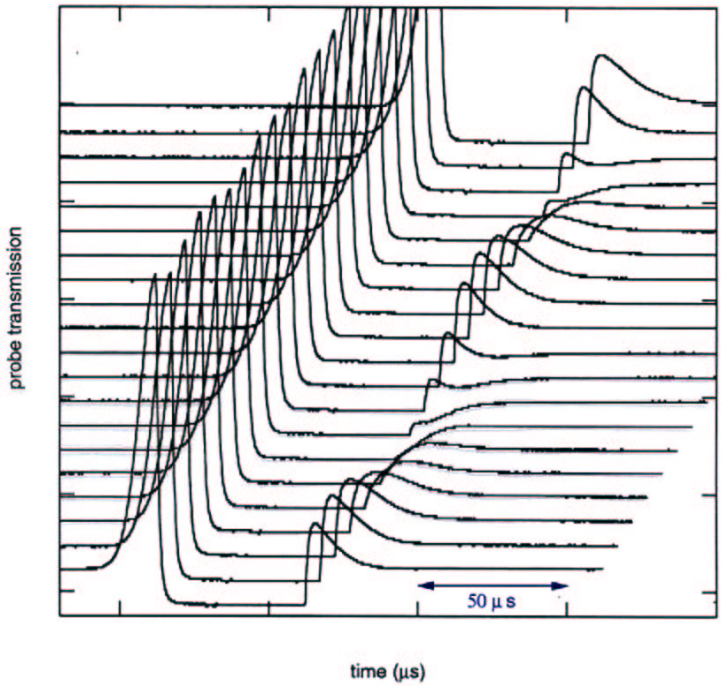
Small bleedthrough of control light



Writing a phase on stored light



Writing a Phase on Stored Light



RAPID COMMUNICATIONS

PHYSICAL REVIEW A, VOLUME 65, 031802(R)

Phase coherence and control of stored photonic information

A. Mair,[1] J. Hager,[1] D. F. Phillips,[1] R. L. Walsworth,[1] and M. D. Lukin[2]
[1]*Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138*
[2]*Department of Physics and ITAMP, Harvard University, Cambridge, Massachusetts 02138*
(Received 9 August 2001; published 14 February 2002)

We report the demonstration of phase coherence and control for the recently developed "light-storage" technique. Specifically, we employ a dynamic form of electromagnetically induced transparency to bring the group velocity of a light pulse to zero, thereby mapping the photonic information into an ensemble spin coherence in warm Rb vapor. We then apply a pulsed magnetic field to vary the phase of the atomic spin excitations and map the altered information back into light. We detect the resultant phase shift in an optical interferometric measurement, thus confirming that the storage process preserves phase coherence.

DOI: 10.1103/PhysRevA.65.031802 PACS number(s): 42.50.Gy, 03.67.−a

The coherent and reversible storage of photon states in matter is an outstanding problem for the practical realization of many basic concepts in quantum information processing. Photons are the fastest and simplest carriers of quantum information, but in general they are difficult to localize and store; for this reason matter (e.g., spins) will likely serve as quantum memory elements. A quantum carrier/memory interface is a key component in the realization of scalable quantum networks [1,2]. In contrast to ordinary techniques which, e.g., destructively convert light intensity into electrical signals by photoabsorption, or transfer angular momentum from polarized light into oriented atomic spins by dissipative optical pumping, a quantum carrier/memory interface would coherently, linearly, and reversibly convert *entire* excitations carried by light pulses into long-lived matter states with minimal dissipation.

Several theoretical proposals have addressed the transfer of quantum states from photons to matter excitations. Early work focused on the use of individual atoms as quantum memory elements [3], and active experimental efforts toward this goal are currently underway [4,5]. However, it was recently realized that quantum state transfer could be simplified by using atomic ensembles [6,7]. In particular, recent experiments employing cold Na atoms [8] and warm Rb vapor [9] demonstrated an important step in this direction: the "storage" of a classical light pulse in an atomic ensemble by the dynamic and reversible reduction of the light pulse group velocity to zero.

The light storage technique is based on a recently proposed [6], dynamic form of the phenomenon of electromagnetically induced transparency (EIT) [10]. In conventional EIT, an external optical field (the "control field") is used to make an otherwise opaque medium transparent near an atomic resonance. A second, weak optical field (the "signal field") at an appropriate frequency and polarization can then propagate without dissipation and loss but with a substantially reduced group velocity [11–13].

In contrast to conventional EIT, the light-storage technique involves the use of a *dynamic* control field. Theoretical work to date [6] indicates that "dynamic EIT" should allow the information in an input pulse of signal light to be linearly, coherently, and reversibly mapped with high efficiency into a collective atomic state without suffering the signal pulse bandwidth limitations imposed in conventional EIT by a static control field [14]. However, the two initial light-storage experiments [8,9] measured only the intensities of the output fields, not the phases. Thus these previous experiments did not show that the light-storage technique provides coherent writing and reading of the signal light pulse into and out of a collective atomic state.

Here we present experimental evidence that the light-storage technique is phase coherent. Although anticipated from theoretical predictions [6], this essential feature of dynamic EIT has not been verified experimentally. Specifically, we demonstrate that the phase of the stored coherence, after being manipulated during the storage interval using standard techniques, is mapped coherently onto the released light pulse. We also demonstrate that light storage is a linear optical process. These results indicate that the present technique should be suitable for applications in quantum information processing, although this remains to be demonstrated with nonclassical (e.g., single photon) states [6]. We note that the light storage technique is an essential component of a recently proposed "quantum repeater" protocol [15] to enable scalable quantum communication over very long distances [16]. Scalable quantum computation using atomic ensembles coupled by light has also been suggested [17].

The present communication can be understood by considering a Λ configuration of atomic states coupled by two optical fields [see Fig. 1(a)]. Here, the control field (Rabi-frequency Ω_c) and signal field (Ω_s) are left and right circularly polarized light (σ^+ and σ^-). Via Raman transitions, these light fields create in the atomic ensemble a coherent antisymmetric superposition of a pair of ground-state Zeeman sublevels ($|-\rangle, |+\rangle$) which have magnetic quantum numbers differing by two. Associated with the reduced group velocity of the signal field is a considerable spatial compression which allows a signal pulse to be almost completely localized in the atomic medium. Inside the medium the light pulse propagates together with the ensemble Zeeman coherence, like a wave of flipped spins. The propagation of the coupled light and spin excitations can be efficiently described in terms of a quasiparticle, the "dark-state polariton" [6], which is a coherent superposition of photonic and spin-wave contributions. In order to store the state of a pulse of signal light, one smoothly turns off the control field, causing

Frequently Asked Questions

- What happens to the speed of light in the cell?
  - The phase velocity is within 1% of c.
  - The group velocity is brought to zero when the light is stored.
- Do we stop photons?
  - The flux of photons out of the cell is equal to that entering.
  - We stop the information.
  - The pulse shape, angular momentum, phase and statistics of the signal field relative to the control field are stored.
- Where does the energy go?
  - The control field carries the energy away.
  - The control field also carries the linear momentum.
- How is this different from a hologram or photon echo?
  - The input pulse can be stored with near perfect efficiency.
  - Theory indicates that it should thus be possible to store quantum states.

Planned experiments to optimize technique

- Additional laser(s) to improve initial state selection
- Investigate buffer gases (also useful for clocks)
- Isotopically enriched ^{87}Rb
- Stronger control beam, faster-switching AOM, and longer vapor cell —> shorter signal pulses

—> *x10 increased optical depth with similar T_2*

—> *store an entire pulse in a vapor cell*

$$\frac{L_{cell}}{L_{pulse}} \leq \sqrt{\alpha}$$ opacity α can be ~ 10^4

Planned probing of "standard" stored light theory

- Can an entire pulse can be stored in a vapor cell?
- Beyond the weak signal field approximation
- Nonadiabatic effects

  $T >> L_{pulse}/c \sim 0.1$ ns
- Light storage robust under large 2-photon detunings

PHYSICAL REVIEW A, VOLUME 65, 022314

Quantum memory for photons: Dark-state polaritons

M. Fleischhauer[1] and M. D. Lukin[2]
[1]*Fachbereich Physik, University of Kaiserslautern, D-67663 Kaiserslautern, Germany*
[2]*Physics Department and ITAMP, Harvard University, Cambridge, Massachusetts 02138*
(Received 29 June 2001; published 15 January 2002)

An ideal and reversible transfer technique for the quantum state between light and metastable collective states of matter is presented and analyzed in detail. The method is based on the control of photon propagation in coherently driven three-level atomic media, in which the group velocity is adiabatically reduced to zero. Form-stable coupled excitations of light and matter ("dark-state polaritons") associated with the propagation of quantum fields in electromagnetically induced transparency are identified, their basic properties discussed and their application for quantum memories for light analyzed.

DOI: 10.1103/PhysRevA.65.022314 PACS number(s): 03.67.−a, 42.50.Gy, 42.65.Tg

I. INTRODUCTION

Recent advances in quantum information science have led to many interesting new concepts such as quantum computation, quantum cryptography, and teleportation [1–3]. The practical implementation of quantum processing protocols requires coherent manipulation of a large number of coupled quantum systems, which is an extremely difficult task. One of the particular challenges for the implementation of these ideas involves physically transporting or communicating quantum states between different nodes of quantum networks [4]. Quantum optical systems appear to be very attractive for the realization of such networks. On one hand photons are ideal carriers of quantum information: they are fast, robust, and readily available. On the other hand atoms represent reliable and long-lived storage and processing units. Therefore the challenge is to develop a technique for coherent transfer of quantum information carried by light to atoms and vice versa. In other words it is necessary to have a quantum memory that is capable of storing and releasing quantum states on the level of individual qubits and on demand. Such a device needs to be entirely coherent, and in order to achieve a unidirectional transfer (from field to atoms or vice versa), an explicit time-dependent control mechanism is required.

Classical optical-data storage in the time domain, based on the phenomenon of spin [5] and photon echo [6], has a long history. After the first proposals of stimulated two-level photon echo [7] and demonstrations of light-pulse storage in these systems [8] many important developments have taken place in this field. Particularly interesting are techniques based on Raman photon echos [9] as they combine the long lifetime of ground-state hyperfine or Zeeman coherences for storage with data transfer by light at optical frequencies [10]. While these techniques promise to be powerful for high-capacity storage of *classical* optical data, they cannot be directly applied for *quantum* memory purposes. The techniques employ direct or dressed-state optical pumping (and thus contain dissipative elements) and typically require that the number of photons is larger than the number of atoms.

The conceptually simplest approach to a *quantum* memory for light is to "store" the state of a single photon in an individual atom. This approach involves a coherent absorption and emission of single photons by single atoms. However, the single-atom absorption cross section is very small, which makes such a process very inefficient. A very elegant solution to this problem is provided by cavity QED [11]. Placing an atom in a high-Q resonator effectively enhances its cross-section by the number of photon round trips during the ring-down time and thus makes an effective transfer possible. Raman adiabatic-passage techniques [12] with time-dependent external control fields can be used to implement a directed but reversible transfer of the quantum state of a photon to the atom (i.e., *coherent* absorption). However, despite the enormous experimental progress in this field [13], it is technically very challenging to achieve the necessary strong-coupling regime. Furthermore, the single-atom system is by construction highly susceptible to the loss of atoms and the speed of operations is limited by the large Q factor.

On the other hand a photon can be absorbed with unit probability in an optically thick ensemble of atoms. Normally such absorption is accompanied by *dissipative* processes, which result in decoherence and thus deteriorate the quantum state. Nevertheless it has been shown that such absorption of light leads to a partial mapping of its quantum properties to atomic ensembles [14,15]. As a consequence of dissipation these methods do not allow to reversibly store the quantum state on the level of *individual* photon wave packets (single qubits). Rather, a stationary source of identical copies is required (e.g., a stationary source of squeezed vacuum, which can be considered as a train of identical wave packets in a squeezed vacuum state) to partially map quantum statistics from light to matter.

Recently we have proposed a method that combines the enhancement of the absorption cross section in many-atom systems with dissipation-free adiabatic-passage techniques [16–18]. It is based on an adiabatic transfer of the quantum state of photons to *collective atomic excitations* using electromagnetically induced transparency (EIT) in three-level atoms [19]. Since the technique alleviates most of the stringent requirements of single-atom cavity QED, it could become the basis for a fast and reliable quantum network. Recent experiments [20,21] have already demonstrated one of the basic principles of this technique—the dynamic group-

Two-photon linewidth of light "stopping" via electromagnetically induced transparency

Claudia Mewes and Michael Fleischhauer
Fachbereich Physik, Univ. Kaiserslautern, D-67663 Kaiserslautern, Germany
(June 4, 2002)

We analyze the two-photon linewidth of the recently proposed adiabatic transfer technique for "stopping" of light using electromagnetically induced transparency (EIT). We show that a successful and reliable transfer of excitation from light to atoms and back can be achieved if the spectrum of the input probe pulse lies within the initial transparency window of EIT, and the two-photon detuning δ is less than the collective coupling strength (collective vacuum Rabi-frequency) $g\sqrt{N}$ divided by $\sqrt{\gamma T}$, with γ being the radiative decay rate, N the effective number of atoms in the sample, and T the pulse duration. Hence in an optically thick medium light "storage" and retrieval is possible with high fidelity even for systems with rather large two-photon detuning or inhomogeneous broadening.

I. INTRODUCTION

One of the challenges of practical quantum information processing and communication is the faithful storage and retrieval of an unknown quantum state in a memory system [1]. Recently we have proposed a technique for a controlled transfer of the quantum state of a photon wavepacket to and from a collective atomic spin excitation [2–4] using electromagnetically induced transparency (EIT) [5] and Raman adiabatic passage [6]. When a weak probe pulse and a much stronger control field couple two metastable states of a 3-level atom through a Raman transition in two-photon (but not necessarily in single-photon) resonance, the control field renders an otherwise optically thick medium transparent. The induced transparency is associated with a substantial reduction of the propagation velocity of the probe pulse due to the formation of a coupled field-spin excitation called dark-state polariton [3,4]. Dynamically reducing the intensity of the control field decelerates the polariton and can bring it to a full stop [7,8]. When the velocity reaches zero, the polariton is entirely matter like and the quantum state of the original light pulse is completely transferred to a collective spin excitation of the atomic ensemble. The process is reversible and the quantum state can be transferred back to a light pulse by reaccelerating the polariton, which can be an exact replica of the original one or — if desired — can occupy different modes (different direction, carrier frequency etc.) [9,10].

Essential for a high fidelity of the transfer process is an explicitly time-dependent control field which varies in most parts adiabatically. When the group velocity of the polariton approaches zero, so does the spectral width of transparency in EIT. Adiabatic following leads however to a narrowing of the spectral width of the probe pulse parallel to the narrowing of the transparency window and thus there are no absorption losses during the slow-down provided the carrier frequency of the probe pulse and the control field are in precise two-photon resonance [4]. For a non-vanishing two-photon detuning the pulse spectrum will move outside the transparency region at some finite value of the group velocity. Thus the question arises what values of the two-photon detuning, if any, are tolerable to maintain a sufficiently high fidelity of the quantum memory. This question is of particular practical importance in gas experiments with different pump and probe frequencies [7,8] or different propagation directions of the fields since two-photon Doppler-shifts are then no longer negligible. An estimate of the two-photon linewidth of light "storage" is furthermore interesting for applications in rare-earth doped solid-state materials with inhomogeneously broadened two-photon transitions [11].

In the present paper we analyze the two-photon linewidth of the storage process based on an analytic perturbation theory and compare it with exact numerical results. We will show that under otherwise favorable conditions, the linewidth is given by the collectively enhanced coupling strength (vacuum Rabi-frequency) $g\sqrt{N}$, with N being the number of atoms divided by $\sqrt{\gamma T}$, with γ being the excited-state decay rate and T the characteristic pulse duration. In an optically thick ensemble this quantity can be large and thus rather large two-photon detunings are tolerable.

II. MODEL

We consider the quasi 1-dimensional system shown in Fig. 1. A probe pulse with positive frequency part of the electric field $E^{(+)}$ couples the transition between the ground state $|b\rangle$ and the excited state $|a\rangle$. $\delta_{ab} = \omega_{ab} - \nu$ is the detuning between the carrier frequency ν and the atomic transition frequency ω_{ab}. The upper level $|a\rangle$ is coupled to the stable state $|c\rangle$ via a coherent control field with Rabi-frequency Ω. $\delta_{ac} = \omega_{ac} - \nu_c$ is the corresponding detuning of the coupling transition. The Rabi-frequency of the coupling field is assumed to be large

Other planned stored light investigations

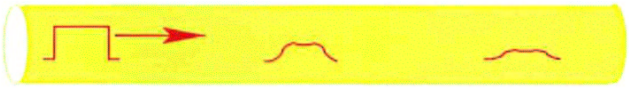
- Effect of decoherence
- Beyond the lambda system: effect of other levels
- Coated vacuum cells

Demonstrate use of stored light technique as a quantum memory

Pursue good new ideas...

Application: quantum communication over long distances

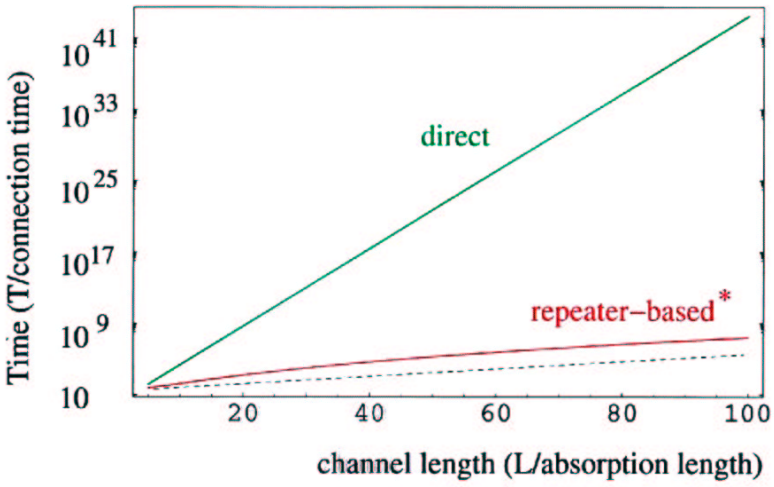
- Signals are attenuated due to absorption and losses



- Solution for classical communication: repeater station

- Quantum signals can not be amplified without adding noise: quantum error correction should be used
- Long distance communication requires quantum network

Quantum communication over long distances: scaling

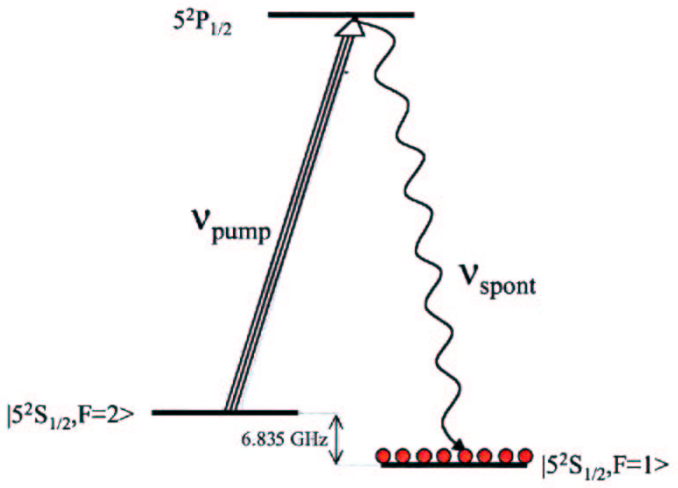


* efficiency of storage + detection ~ 50 % is assumed

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

Demonstration of single-quantum storage

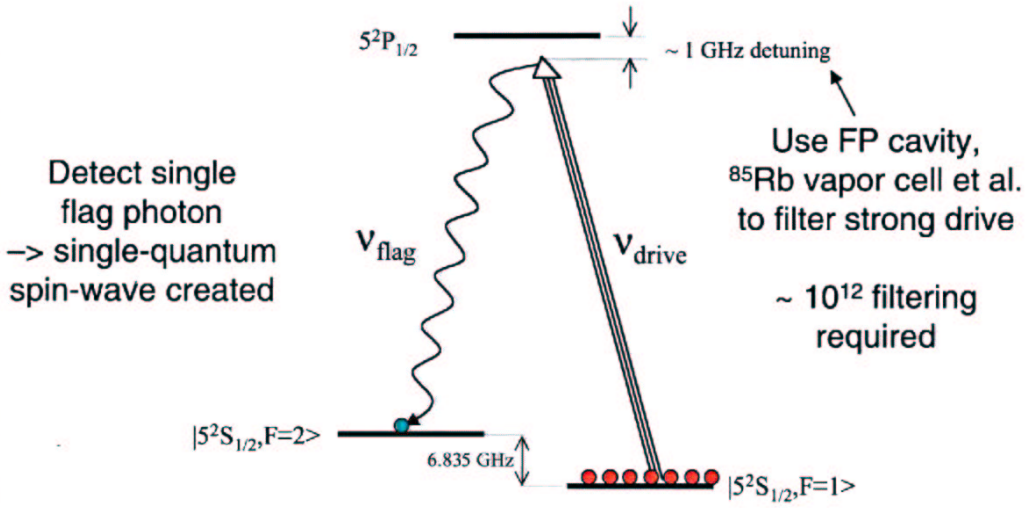
Step 1: optically pump



^{87}Rb D_1 line (795 nm)

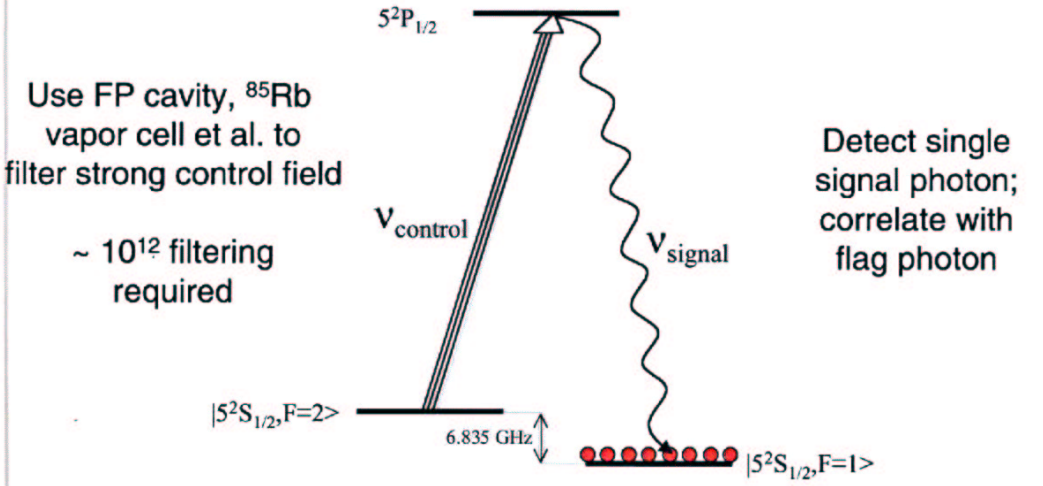
Demonstration of single-quantum storage

Step 2: single-quantum spin-wave excitation
via off-resonant spontaneous Raman scattering



Demonstration of single-quantum storage

Step 3: use stored light release technique to convert
single-quantum spin-wave into a single resonant photon



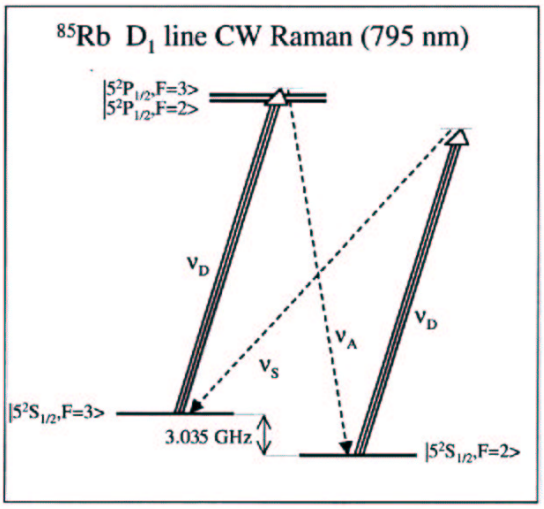
Photon statistics of near-resonant Raman-scattering

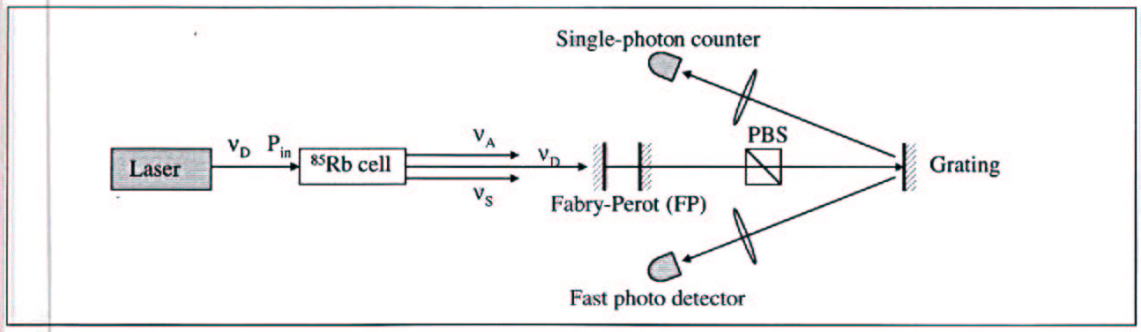
Recent results:

- We can isolate a single mode of Raman light co-propagating with an intense drive field shifted by 3 GHz.
- Raman fields show crossover from Bose-Einstein (thermal) to Poisson (coherent) statistics when drive intensity is increased.
- Residual drive field has strong intensity fluctuations, even though only a few percent of the drive field is Raman scattered. Raman modes create a fluctuating EIT window for drive field?
- Fluctuations in transmitted drive and Raman fields show strong classical correlations.
- Test for quantum correlations in progress.

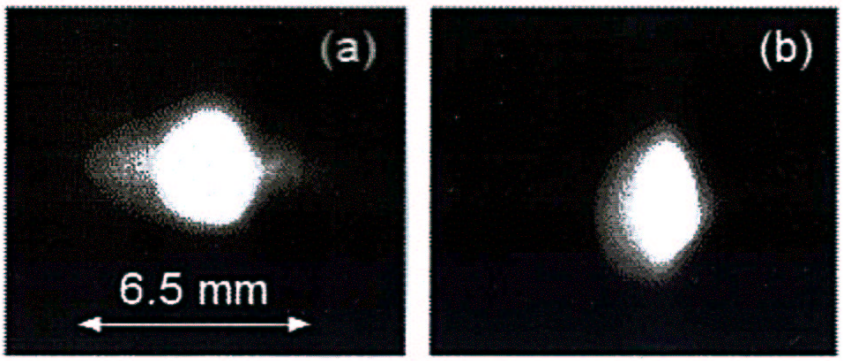
Experimental setup

- Four-wave mixing scheme
- Near-resonant input drive field, $P_{in} \approx 5$ mW
- ^{85}Rb vapor cell ($T \approx 100$ °C, $n \approx 10^{12}$ cm^{-3})
- Residual drive (ν_D), Stokes (ν_S), and Anti-Stokes (ν_A) fields leave vapor cell (each typically 10 – 100 μW power)
- Fabry-Perot, grating, interference and color filters, and pinholes are used to detect one mode of the output fields and to suppress background signals





Far-field images of drive and Raman fields

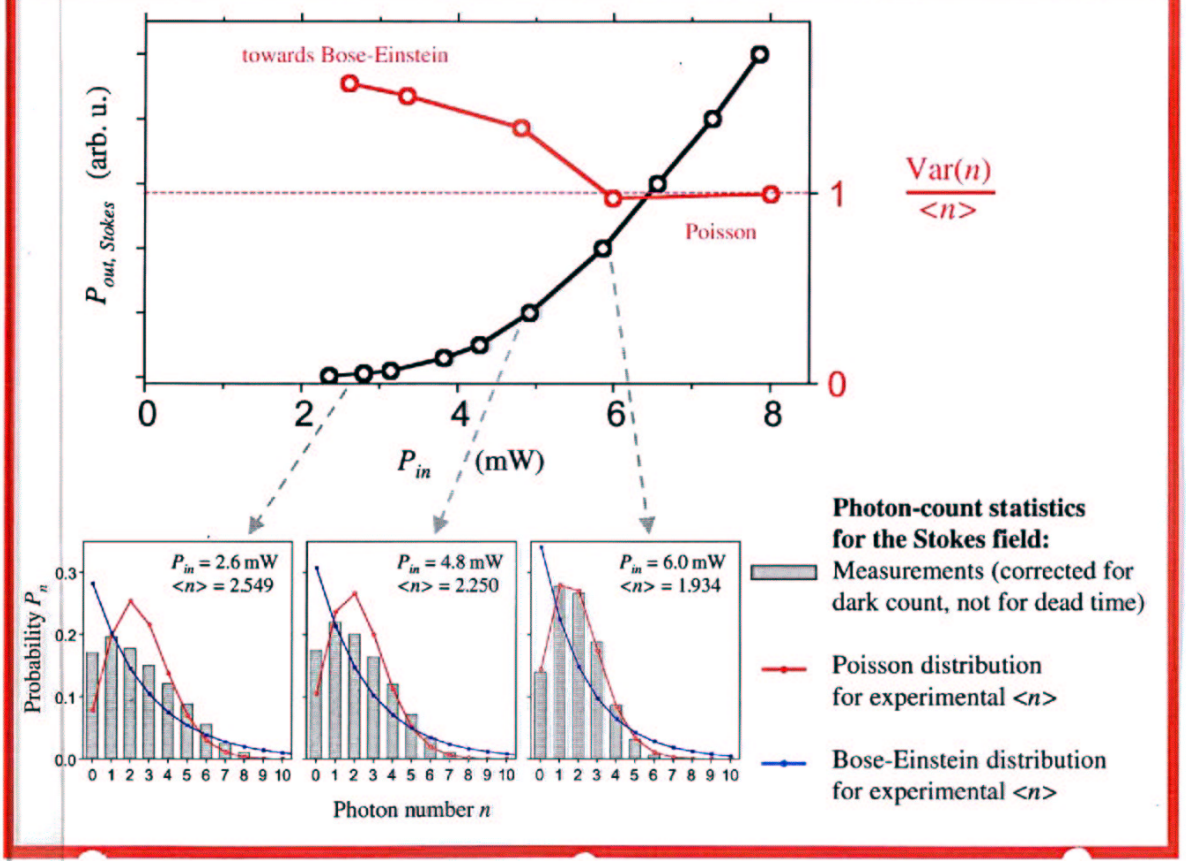


(a) Raman fields are concentrated in side modes that (almost) co-propagate with the drive field.

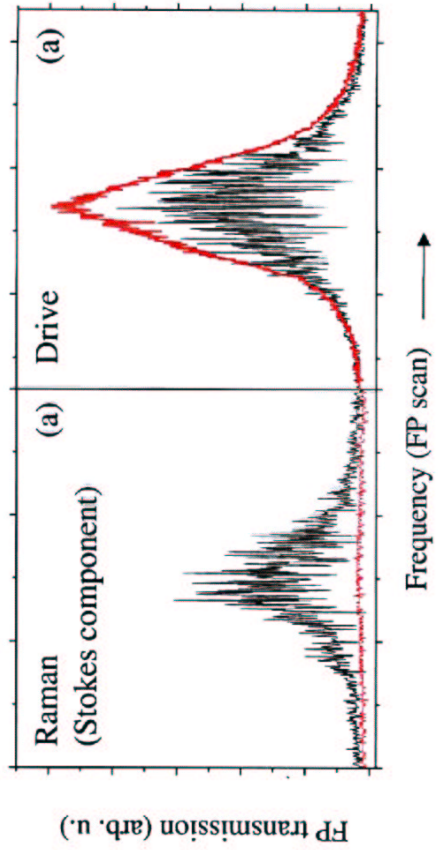
(b) Raman scattering is suppressed by applying a magnetic field.

Enhancement of refractive index, phase-matching condition $2\vec{k}_D = \vec{k}_S + \vec{k}_A$
—> resonant anti-Stokes light propagates inside waveguide induced in medium
non-resonant Stokes light escapes waveguide

Asymmetry of Raman light due to astigmatism of low-power laser diode



- Transmitted drive field fluctuations are similar to that of Raman fields.
- Raman modes create a fluctuating EIT window for the drive field?
  [M. D. Lukin *et al.*, PRL **81**, 2675 (1999)].
- Strong classical correlations between fluctuations in the residual drive and Raman fields.



Black data show noise on transmission spectra of the Stokes field (a), and drive (b). When Raman scattering is suppressed with a magnetic field the noise vanishes (Red data).

Manipulating Light Pulses via Dynamically controlled Photonic Bandgap

A. André and M. D. Lukin
Physics Department and ITAMP, Harvard University, Cambridge, Massachusetts 02138
(May 14, 2002)

When a resonance associated with electromagnetically induced transparency (EIT) in an atomic ensemble is modulated by an off-resonant standing light wave, a band of frequencies can appear for which light propagation is forbidden. We show that dynamic control of such a bandgap can be used to coherently convert a propagating light pulse into a stationary excitation with non-vanishing photonic component. This can be accomplished with high efficiency and negligble noise even at a level of few-photon quantum fields thereby facilitating possible applications in quantum nonlinear optics and quantum information.

PACS numbers 03.67.-a, 42.50.-p, 42.50.Gy

Techniques for coherent control of light-matter interaction are now actively explored for storing and manupilating quantum states of photons. In particular, using electromagnetically induced transparency (EIT) [1,2] and adiabatic following of "dark-state polaritons" [3], the group velocity of light pulses can be dramatically decelerated and their quantum state can be mapped onto metastable collective states of atomic ensembles [4].

In contrast to such a coherent absorption process, the present Letter describes how a propagating light pulse can be converted into a stationary excitation with non-vanishing photonic component. This is accomplished via controlled modification of the photonic density of states in EIT media by modulating the refractive index with an off-resonant standing light wave. By varying the properties of the resulting photonic band structure in time, the original light pulse can be converted into an excitation inside the bandgap where its propagation is forbidden. Long storage of excitations with non-vanishing photonic component may open interesting prospects for enhancement of nonlinear optical interactions [5,6]. In particular, an intriguing and practically important [7,8] application of this effect for interactions between few-photon fields is dicussed in the concluding paragraph of this Letter.

Before proceeding, we note that there exists a substantial litterature on photonic bandgap [9] materials. Recently photonic bandgap structures have been investigated theoretically [10] for strong coupling of single atoms with photons. Photonic bandgap based on interaction with atoms in an optical lattice were also investigated [11]. We also note other related work on EIT-based control of the propagation properties of light in atomic media [12].

The key idea of the present approach can be qualitatively understood by first considering a medium consisting of stationary atoms with a level structure shown in Fig. 1a. The atoms are interacting with a weak signal field and two strong fields. The running wave control field Ω_c is tuned to resonant frequency of the $|b\rangle \rightarrow |c\rangle$ transition. In the absence of the field Ω_s, this situation corresponds to the usual EIT: in the vicinity of a frequency corresponding to two-photon resonance the medium becomes transparent for a signal field. This transparency is accompanied by a steep variation of the refractive index.

The dispresion relation can be further manipulated by applying an off-resonant standing wave field with Rabi frequency $\Omega_s(z) = 2\Omega_s \cos(k_s z)$ and a frequency detuning Δ. This field induces an effective shift of resonant frequency (light shift) that varies periodically in space, resulting in a spatial modulation of the index of refraction according to $\delta n(z) = (c/v_g) 4\frac{\Omega_s^2}{\Delta} \cos^2(k_s z)$, where c/v_g is the ratio of speed of light in vacuum to group velocity in the medium. When the modulation depth is sufficiently large, signal light propagating near atomic resonance in the forward z direction with wavenumber k near k_s may undergo Bragg scattering into the backward propagating mode with wavenumber $-k$. In direct analogy to e.g., optical interferometers, the scattering of the counterpropagating fields into each other can modify the photonic density of states. In particular, a range of frequencies ("photonic bandgap") can appear for which light propagation is forbidden [13]. According to a standard technique to analyze the resulting band structure, Bloch's theorem can be applied so that the propagating solutions obey $E(z+a) = e^{iKa}E(z)$, where K is the Bloch wave vector. Imposing this condition and assuming that the wave vectors of the fields are close ($k \simeq k_s$), we can solve for the band structure and obtain near two-photon resonance

$$\cos(Ka) = \cosh\left(\frac{g^2 N}{\Omega_c^2} a \sqrt{\Delta_s^2 - (\omega - \omega_{ba})^2}\right), \quad (1)$$

where $g = \wp\sqrt{\frac{\nu}{2\hbar\epsilon_0 V}}$ is the atom-field coupling constant, N is the number of atoms, $\Delta_s = \Omega_s^2/\Delta$ is the amplitude of the light shift modulation, $\wp$ is the dipole moment of the $a-b$ transition, V the quantization volume and the factor $g^2 N/\Omega_c^2$ corresponds to c/v_g. For frequencies such that $|\omega - \omega_{ba}| \leq |\Delta_s|$ a *bandgap* is created: the Bloch wavevector acquires an imaginary part and the propagation of waves in the medium is forbidden. For an outside observer such a medium can be viewed as a mirror: an incident wave with frequency inside the bandgap would

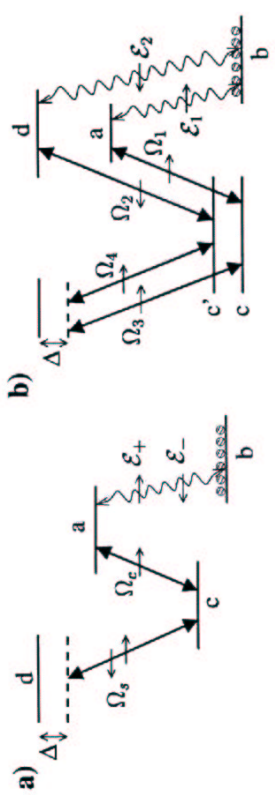


FIG. 1. Atomic level configuration for EIT-induced photonic bandgap. a) Stationary atoms scheme, b) moving atoms scheme. The standing wave of Rabi frequency Ω_s is detuned by Δ from resonance with the $|c\rangle \rightarrow |d\rangle$ transition, giving rise to a spatially modulated light shift $\Delta_s(z,t) = |\Omega_s(z,t)|^2/\Delta$.

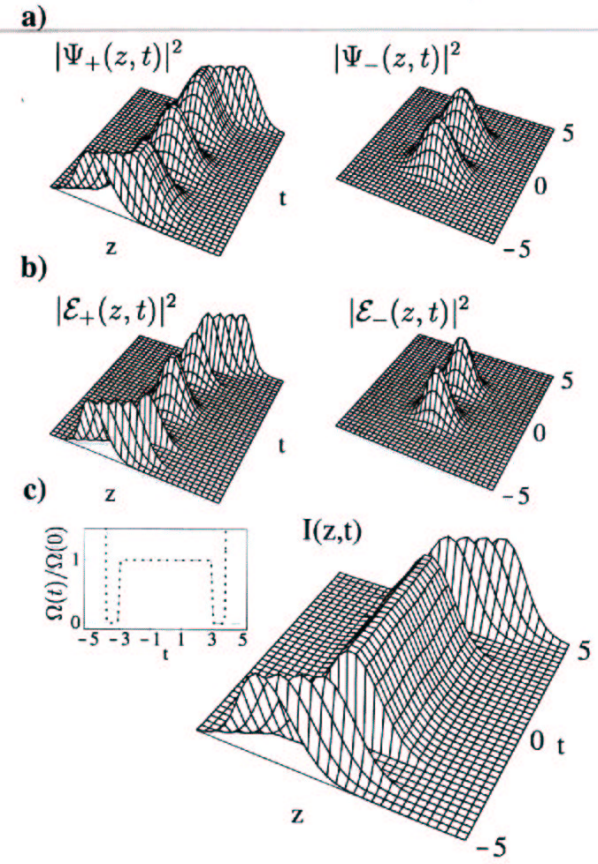


FIG. 3. a) Amplitude of forward and backward propagating polaritons $\Psi_+(z,t)$ and $\Psi_-(z,t)$. b) Corresponding electric fields and c) total intensity (forward and backward components) averaged over the optical wavelength. Also shown is the time-dependence of the "control" field $\Omega_c(t)$ (dotted line) and of standing wave field $\Omega_s(t)$ (dashed line). Note that $v_g^{in}/v_g^0 \sim 15$ here so that initial motion of the pulse is noticeable on these plots. Axes are in arbitrary units.

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Coherent Atom Interactions Mediated by Dark-State Polaritons

A. André,[1] L.-M. Duan,[2] and M. D. Lukin[1]

[1]*Physics Department, Harvard University, Cambridge, Massachusetts 02138*

[2]*Institute for Quantum Information, California Institute of Technology, Pasadena, California 91125-8100*

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We suggest a technique to induce effective, controllable interactions between atoms that is based on Raman scattering into an optical mode propagating with a slow group velocity. The resulting excitation corresponds to the creation of spin-flipped atomic pairs in a way that is analogous to correlated photon emission in optical parametric amplification. The technique can be used for fast generation of entangled atomic ensembles, spin squeezing, and applications in quantum information processing.

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The intriguing possibility for controlled manipulation of interacting quantum systems is the basis for a number of exciting developments in the field of quantum information science [1]. These are expected to have an impact in a broad area ranging from quantum computation and quantum communication [2] to precision measurements [3] and controlled modeling of complex quantum phenomena [4].

This Letter describes a new technique to induce effective coherent interactions between atoms in metastable states. The technique is based on a resonantly enhanced nonlinear process involving Raman scattering into a "slow" optical mode [5], which creates a pair of spin-flipped atoms and slowly propagating coupled excitation of light and matter (dark-state polariton). When the group velocity of the polariton is reduced to zero [6,7], this results in pairs of spin-flipped atoms.

The present phenomenon of spin pair creation exhibits strong similarities with optical parametric amplification (OPA), in which pairs of photons are generated that possess nonclassical correlations in photon number, quadrature component fluctuations, or polarization states [8]. In direct analogy, the present technique is capable of generating nonclassically correlated atomic ensembles and entangled spin excitations. The latter can easily be converted into corresponding states of photon wave packets "on demand," which makes the present approach most suitable for implementing protocols in quantum information processing that require a combination of deterministic sources of entangled states and long-lived quantum memory [9,10].

The present technique can also be viewed as a new mechanism for coherent "collisions" [11] between atoms mediated by light. In particular, the case when atomic pairs are excited into two different levels (as, e.g., in Fig. 1a) closely resembles coherent spin-changing interactions that occur in degenerate atomic samples [12], whereas the case when atomic pairs are stimulated into identical states (Fig. 1b) is reminiscent of dissociation of a molecular condensate [13]. To put this analogy in perspective we note that the rate of the present optically induced process can exceed that of weak interatomic interactions by orders of magnitude. Therefore the present work may open up interesting new possibilities for studying many-body phenomena of strongly interacting atoms.

Before proceeding we note that a number of proposals have been made for generating entangled states of atomic ensembles. Some are based on interatomic interactions at ultracold temperatures [14], whereas others involve mapping the states of nonclassical light fields into atoms [15], quantum nondemolition measurements of spins [16] with light, and Rydberg blockade [17]. Also note the recent experiments on number-phase squeezed states and the Mott insulator phase in Bose-Einstein condensation [18]. In contrast to these mechanisms the present approach does not require coherence of the atomic motion or sources of nonclassical light and is completely deterministic thereby significantly simplifying possible experimental realizations. We further show that the present technique can be made robust with respect to realistic decoherence processes such as spontaneous emission and leakage of slow photons from the medium. Note that the present mechanism does not rely on so-called "photon exchange" interactions discussed by Franson *et al.* [19,20].

We consider a system of N atoms (Fig. 1) interacting with two classical driving fields and one quantized mode that is initially in a vacuum state. Relevant atomic sublevels include two manifolds of metastable states (e.g., hyperfine sublevels of electronic ground state) and excited states that might be accessed by optical transitions. The atoms are initially prepared in their ground states $|g\rangle$. One of the classical fields (Rabi frequency Ω_1) is detuned from

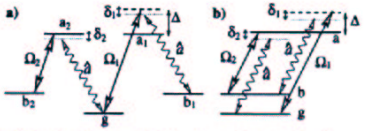

FIG. 1. Level scheme for the coherent interaction leading to pairs of atoms in (a) different final states $|b_2\rangle$ and $|b_1\rangle$, (b) the same final state $|b\rangle$.

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Atom correlations and spin squeezing near the Heisenberg limit: finite size effect and decoherence

A. André and M.D. Lukin

Physics Department, Harvard University and

ITAMP, Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138

(December 24, 2001)

We analyze a model for spin squeezing based on the so-called counter-twisting Hamiltonian, including the effects of dissipation and finite system size. We discuss the conditions under which the Heisenberg limit, i.e. phase sensitivity $\propto 1/N$, can be achieved. A specific implementation of this model based on atom-atom interactions via quantized photon exchange is presented in detail. The resulting excitation corresponds to the creation of spin-flipped atomic pairs and can be used for fast generation of entangled atomic ensembles, spin squeezing and applications in quantum information processing. The conditions for achieving strong spin squeezing with this mechanism are also analyzed.

PACS numbers 03.67.-a, 42.50.-p, 42.50.Gy

I. INTRODUCTION

Interacting quantum systems that start in uncorrelated states generally evolve towards entangled states due to quantum correlations building up in time. These correlations and the form they take depend crucially on the interaction that gives rise to them. For example in parametric down conversion or in the optical parametric oscillator (OPO) pairs of photons can be created in distinct modes of the electromagnetic field. The fact that *pairs* of photons are generated leads to quantum correlations between the two modes. Since each mode is described by a harmonic oscillator, one can think of the state of the field as the quantum state of two fictitious particles in harmonic oscillator potentials. The quantum correlations correspond to e.g. the positions of the particles being strongly correlated, in the ideal case $\Delta(X_1 - X_2)^2 \to 0$ and their momenta being anticorrelated $\Delta(P_1 + P_2)^2 \to 0$. For the electromagnetic field modes, the position and momenta correspond to quadratures of the field modes and it is between these that correlations are produced [1,2]. These correlations are essential to quantum communication e.g. quantum teleportation of information from one location to another [3]. Entanglement is also crucial for many schemes in quantum cryptography and for long-distance quantum communication through lossy channels [4].

Since the mechanism for producing correlations in electromagnetic field modes is at the fundamental level so simple (photons created in pairs) it is natural to wonder if such a simple mechanism may lead to entanglement of atoms interacting in a similar manner. In complete analogy to the OPA mechanism, a process that transfers *pairs* of atoms from their ground state to two well defined final states also gives rise to quantum correlations between atoms. When a collection of N two level atoms is thought of as an ensemble of effective spin $\frac{1}{2}$ particles with total pseudo-angular momentum $J = N/2$, it turns out [5] that the quantum correlations produced by an interaction that transfers atoms in pairs from the lower state to the upper state shows up as reduced fluctuations in a component of the angular momentum e.g. $\Delta J_x^2 \to 0$. We will discuss entanglement of atoms with one another in an atomic ensemble for which an effective interaction leads to the transfer of atoms in pairs to well defined final states and we will use the concept of spin squeezing to quantify the amount of quantum correlations produced in such a case. As for squeezed states of light, decoherence mechanisms and dissipation are acting in such a way as to destroy or limit the amount of squeezing achievable in practice. We also analyze the influence of such dissipation mechanisms and find relations between the spin squeezing interaction rate, the dissipation rate and the amount of squeezing achievable in the presence of damping mechanisms. The coherent control of the dynamical evolution of complex systems such as atomic ensembles may lead to the production of entangled nonclassical states such as spin squeezed states [5] (analogous to squeezed states of light [2]) and correlated collective atomic modes (similar to twin photons generated by a non-degenerate OPO).

The main result of this paper is that for a collection of N atoms with average single atom nonlinearity χ (two atom interaction energy) and with single atom loss rate Γ, the condition for achieving some spin squeezing is that $N\chi > \Gamma$. In order to achieve reduction of uncertainty in say J_x compared to the uncertainty in the Bloch state $|J = N/2, J_z = N/2\rangle$ for which $(\Delta J_x)^2 = N/4$ by an amount s (i.e. $(\Delta J_x)^2 = N/(4s)$) with $1 \le s \le N$, one requires that $N\chi > s\Gamma$ and the interaction time needed scales as $t \sim (\log s)/(N\chi)$ while the maximum number of atoms than can be lost without destroying the squeezing scales as $\Delta N \sim (N/s)\log s$. To achieve Heisenberg limited precision (i.e. maximum spin squeezing $s \sim N$), one needs a large single atom nonlinearity $\chi > \Gamma$. This means that the interaction time needed to achieve this strongly correlated state is $t \sim (\log N)/(N\chi)$ and the maximum

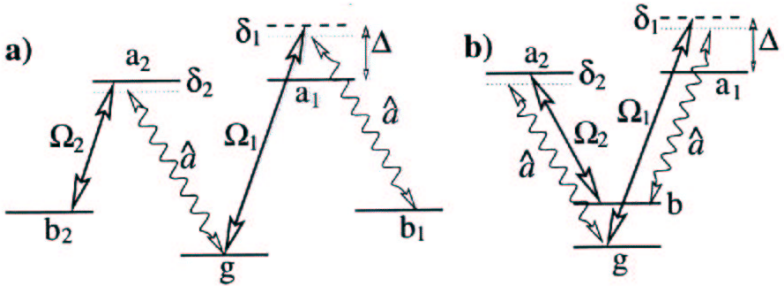

FIG. 4. Energy levels scheme for the effective coherent interaction leading to creation of pairs of atoms a) in different final states ("non-degenerate" scheme) and b) in identical final states("degenerate" version).

Update on Walsworth/Lukin "stored light" collaboration at Harvard

- Context: who, what, where, when…
- Review of first stored light demos in vapor cells:
  - *classical light pulses*
  - *phase coherence and control*
- Planned experiments to test theory & optimize technique
- Outline of plan to demonstrate single-quantum storage
- Recent measurements of statistics of Raman light
- Maybe a brief word about our CPT clock work
- Some recommended theory papers