University *of Ljubljana*
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Quantum memory with cold atoms in a magnetic field

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Abstract

In a quantum memory experiment, one wishes to store information, usually in the form of light, as efficiently and for as long a time as possible. For this, a cold-atoms based quantum memory using electromagnetically induced transparency has great potential. However, in experiments with cold atoms, it is difficult to completely nullify residual magnetic fields, which causes periodic oscillations in the amplitude of the retrieved light. This happens because the magnetic sublevels of the atoms are no longer degenerate. These periodic oscillations can discretize the retrieval ability and even effectively shorten the storage time. In this seminar, I demonstrate that by deliberately turning on a strong magnetic field and polarizing the atoms into one of the stretched magnetic states, the achieved storage time can be increased tenfold, to more than 400 µs.

Contents

1 Introduction

The ability to coherently store light and to recall it at a later time is essential for quantum communication [1, 2]. For this purpose, quantum memories have been subject to a lot of research in recent years [3, 4]. The idea behind such a quantum memory is to store a photon (or a number of photons) in a material medium (most often dense atomic clouds or doped solids [5]) for a desired time, with the ability to recall it at will.

A number of methods for a quantum memory have been developed and explored. Broad-band Raman memories have proven to be useful as high-bandwidth on-demand single photon sources with efficiencies of about 30 % [6]. Duan–Lukin–Cirac–Zoller (DLCZ) schemes have been used for broad-band single photon storage in room temperature atoms with an exceptionally good signal-to-noise ratio [7]. Gradient echo memories can reach very high efficiencies, up to 87 % [8] and storage times up to 0.6 ms [9]. In recent years, the use of electromagnetically induced transparency (EIT) on hot and cold atoms has been shown to be a very promising, although narrowband, method [10, 11], with achieved lifetimes on the timescale of minutes [12] and efficiencies of around 80 % [13]. However, in such experiments, stray magnetic fields are often present, which change the conditions of the EIT drastically. While a lot of research has been done on this as well [14, 15, 16], not much research has been put into how to optimize the quantum memory in a magnetic field or even how to improve the memory by turning on magnetic fields on purpose.

In this seminar, we first explain the theory behind EIT and how magnetic fields influence the storage. Then, we focus on experimental work, wherein we show how the effective lifetime of the quantum memory can be improved by applying a homogeneous magnetic field on unpolarized cesium cold atoms. Then we show how polarizing the atoms in an even stronger magnetic field suppresses storage collapses which arise in the presence of magnetic fields, overall increasing the quantum memory lifetime tenfold.

2 Theory

Electromagnetically induced transparency occurs when two laser beams that form a Λ-type system (Fig. 1a) are shone onto a dense cloud of atoms. These beams drive a two-photon transition from the ground state to the storage state via an excited state. The signal beam couples the ground state to an excited state, while the control beam couples the storage and excited state. The signal beam is much weaker than the control beam, and the transition between the storage state and the ground state must be dipole-forbidden. Under these conditions, the absorption of the signal beam is greatly reduced, and the refractive index undergoes a steep variation at the resonance frequency (Fig. 1b). This leads to a strong reduction of the group velocity of the signal beam, causing a phenomenon called slow light [17, 18, 19].

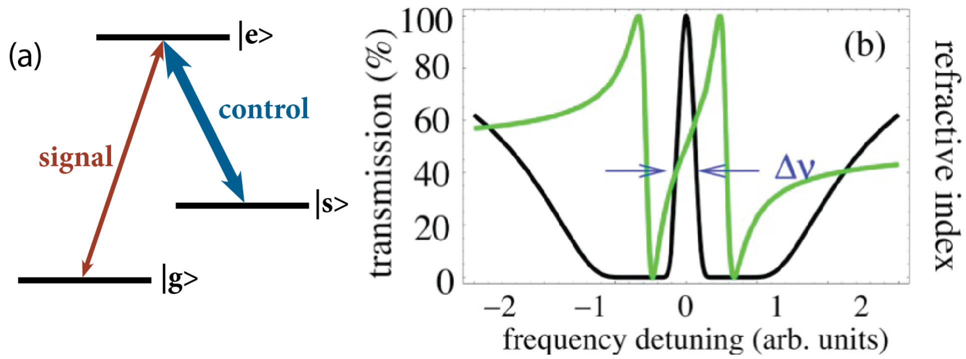

Figure 1: (a) shows a Λ-type system. Ω_s and Ω_c denote the Rabi frequencies of the signal beam and the control beam, respectively. The signal beam couples the ground state $|g\rangle$ to the excited state $|e\rangle$ and the control beam couples the excited state to the storage state $|s\rangle$. (b) shows the transmission of the signal beam (black) and the refractive index of the medium (green) in the EIT configuration as a function of frequency detuning between the two beams. (b) was taken from Ref. [20].

A pulse of the signal beam, slowed down by EIT, can be described as a quasi-particle called a dark-state polariton (DSP), represented by a wave function $\psi(z, t)$ [21]. It has an electromagnetic component (denoted by $E(z, t)$), which describes the light pulse, and an atomic component, which is given by the state of the atoms and is represented by the atomic projection operator of the ground and storage states $\sigma_{gs}(z, t)$. While the signal pulse is slowly propagating through the atoms, the stronger beam, called the control beam, can be adiabatically turned off. This causes the electromagnetic part of the DSP, along with the group velocity of the signal pulse, to be reduced to zero (see Fig. 2). The information of the signal pulse is thus stored in the spin coherence between the ground state and the storage state. This coherence is called a spin-wave and evolves temporally with a frequency $\omega_{sw} = \omega_s - \omega_g$, where $\hbar\omega_s$ and $\hbar\omega_g$ are the energies of the storage and ground states. For our experiment, this frequency is 9.193 GHz if there is no magnetic field present.

After a desired time, adiabatically turning the control beam back on transfers the information from the atomic component of the DSP back into the electromagnetic component and the signal pulse is restored [15, 22, 23].

For the ideal quantum memory, a high efficiency and a long time of storage are desired. The latter is greatly affected by the movement of the atoms [24, 25] and any magnetic gradients that might be present [26]. While annulling stray-field gradients is hard, especially in cold atom experiments, deliberately turning on a strong perpendicular homogeneous magnetic field has been shown to actually improve the lifetime of cold atom-based quantum memories [16]. However, a weak residual magnetic field may cause the atomic states to undergo Zeeman splitting and the Λ-systems are no longer degenerate (see Fig. 3a).

Consequently, once we turn off the control beam to store the signal pulse, many spin-waves with different energies $\hbar\omega_{sw}$ are formed (Fig. 3b). Because these spin-waves evolve with different frequencies, they interfere with each other. Depending on when we turn the control beam back on, this causes collapses and revivals of the amplitude of the retrieved light pulse as a function of storage time. Weak magnetic fields (e.g., a couple mG $\approx$ 100 nT from residual fields in cold-atom experiments) cause the time between revivals to be large [14, 15]. This may result in only the initial collapse being visible, as the consequent revivals

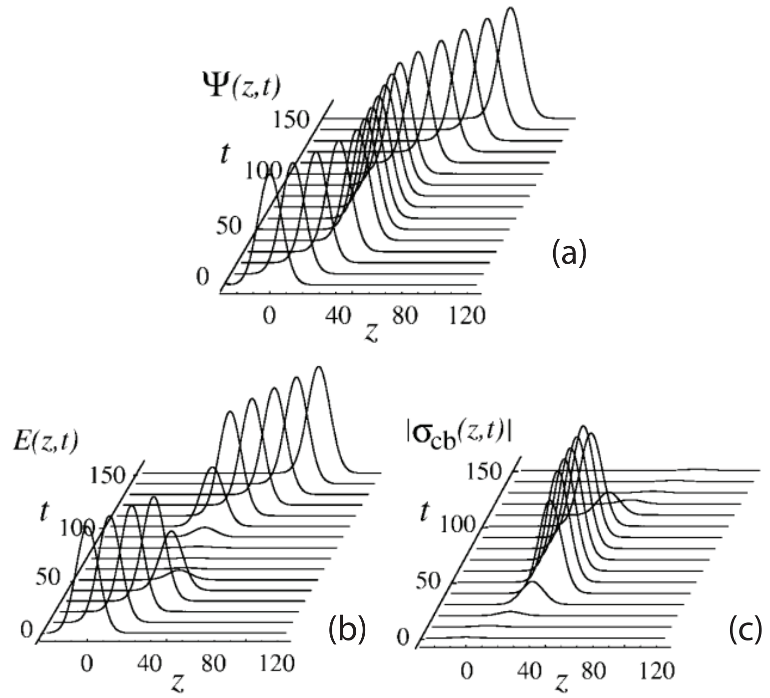

Figure 2: Propagation of a dark-state polariton through space (z) and time (t). (a) shows the propagation of the DSP amplitude as a whole, while (b) shows the amplitude of the electric field and (c) shows the evolution of the atomic component. At $t \approx 30T$, we store the signal pulse in the atoms and at $t \approx 110T$ we turn the control beam back on to retrieve the stored pulse. The time t is normalized with a characteristic time T, which is much shorter than the decoherence time and large enough that the control beam change is adiabatic. Adapted from Ref. [21].

of the stored light amplitude are further than the intrinsic lifetime of the memory allows. Therefore, the effective lifetime of the quantum memory is much shorter than if there was no magnetic field present. If, however, we turn on a stronger magnetic field (around 100 mG), the time between revivals decreases and much longer lifetimes are achievable, limited now mostly by just the atomic motion. Gradients of this strong magnetic field still contribute to the decoherence of the memory, but the components of the perpendicular fields and their effects become negligible, overall decreasing the decoherence due to magnetic field gradients [16].

There remains one major challenge. Due to these collapses of stored light amplitude between the revivals, the quantum memory is, in a way, discretized. The question, therefore, is how to reduce these collapses so that the quantum memory can be used for all storage times.

3 Experiment

We prepare a cloud of 5×10^7 cesium atoms in a magneto-optical trap (MOT) at $\sim 20\,\mu$K, with the procedure described in Ref. [27]. We start the quantum memory 4 ms after turning off MOT, when the quadrupole field is practically zero. The desired magnetic fields for the experiment are then controlled by three pairs of large Helmholtz coils. The experimental setup for the quantum memory is shown in Fig. 4.

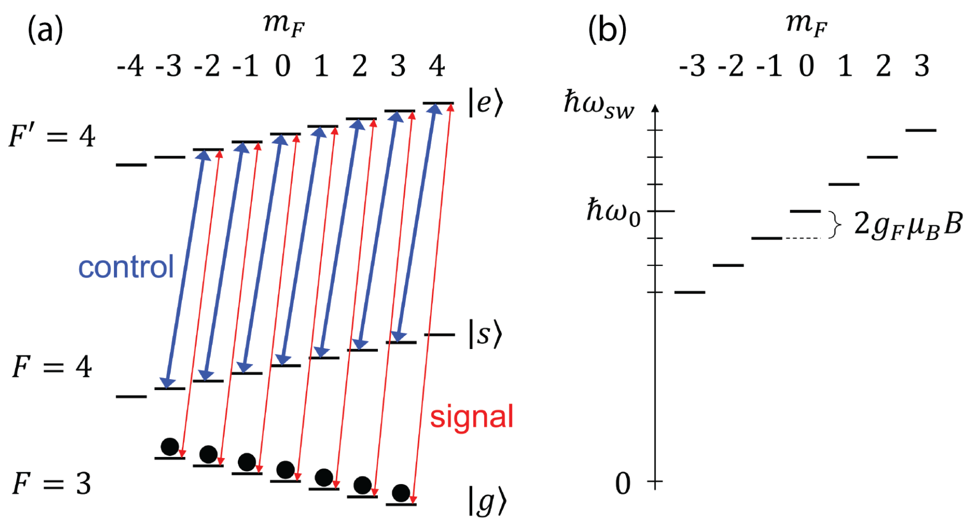

Figure 3: Energy levels of Cs D_2 transition used for EIT. The control beam drives the transition $|F = 4\rangle \to |F' = 4\rangle$ and the signal beam is on the $|F = 3\rangle \to |F' = 4\rangle$ transition. Both beams are σ^+ polarized, as in the second part of the experiment. (a) In the presence of a magnetic field, the m_F levels are not degenerate due to Zeeman splitting. In this case, seven different Λ systems contribute to the quantum memory, each creating its own spin-wave with a slightly different energy. The energies of the spin-waves are shown in (b).

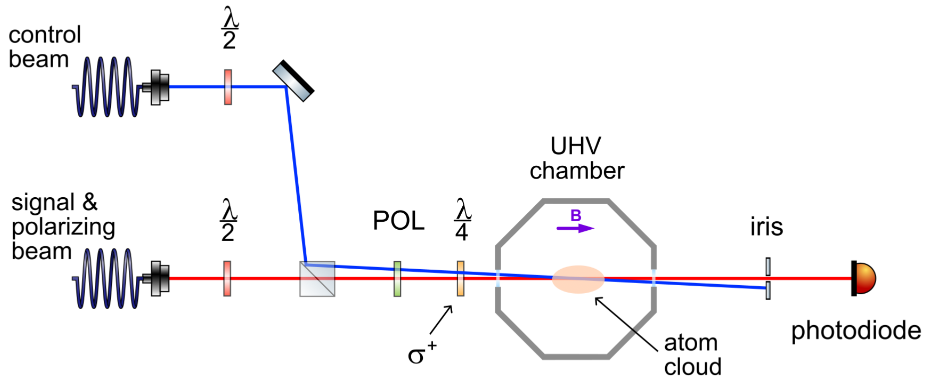

Figure 4: Experimental setup for section 3.2. We prepare the beams on a different optical table and bring them to the cold atoms trough optical fibers. We combine the control and signal beam on a polarizing beam splitter and set both polarizations to σ^+ with a polarizer and a quarter-wave plate. The two beams travel at an angle of $\sim 1°$ to enable spatial filtering of the control beam, and intersect at the position of the atomic cloud in the ultra-high vacuum chamber. On the other side of the chamber, we block the control light with an iris and measure the intensity of the signal beam with a photodiode. To polarize the atoms, we shine a σ^+-polarized polarizing beam onto the atoms from the same fiber as the signal beam. The magnetization axis is determined by a magnetic field $B \sim 100\,\text{mG}$, parallel to the polarizing beam. $\lambda/2$ denotes a half-wave plate.

In all the following experiments, we shine on the atoms with the control beam and send in a $0.5\,\mu\text{s}$ signal pulse. Along with the end of the pulse, we turn off the control beam as well. After the desired storage time, we adiabatically turn the control beam back on to retrieve the stored light.

3.1 Non-polarized atoms

First, we demonstrate the effect a magnetic field has on an EIT-based quantum memory with non-polarized atoms. In this part of the experiment, the magnetic field is perpendicular to the direction of the signal beam and the polarizing beam is turned off. The beams are both circularly polarized, but in opposite directions: the signal beam is σ^+ polarized while the control beam is σ^- polarized. Having the beams polarized in this way ensures that the atoms stay equally distributed across all m_F sublevels throughout the experiment. For the detection of the retrieved light after turning the control beam back on, we separate the beams spatially (there is a $\sim 1^\circ$ angle between them) as well as with a polarizing beam splitter.

The amplitude of the retrieved light for non-polarized atoms evolves temporally as [23]

$$A(t) = A(0) \left| \sum_{n=-3}^{3} \sum_{m=-4}^{4} P_{n,m} \mathrm{e}^{i(\omega_0 + (n+m) g \mu_B B/\hbar) t} \right|^2 \mathrm{e}^{-t/\tau}, \tag{1}$$

where $A(0)$ is the initial amplitude of the stored light. n and m sum over the magnetic sublevels of the ground state $|F = 3\rangle$ and the storage state $|F = 4\rangle$, and $P_{n,m}$ represent the amplitudes of coherences between sublevels n and m. A photon involved in an atomic transition can change the magnetic number for at most one, and these are two-photon coherences, therefore the only non-zero amplitudes are those for $|n - m| \leq 2$. ω_0 is the frequency difference between the ground and storage states $|F = 3\rangle$ and $|F = 4\rangle$ in zero magnetic field. For cesium, this frequency is 9.193 GHz. $g = 0.35\,\mathrm{MHz/G}$ is the Landé g-factor for $|F = 3\rangle$, and for $|F = 4\rangle$, the factor is of equal magnitude and opposite sign [28], which has already been taken into account in Eq. 1. μ_B is the Bohr magneton and B is the magnetic flux density. τ is the storage lifetime.

We measure the efficiency of the quantum memory for storage times up to 60 µs for different magnetic flux densities. The results are show in Fig. 5. We notice that the revival peaks occur with a frequency of $2\pi/\omega_L$, where $\omega_L = g\mu_B B/\hbar$ is the Larmor frequency. Notably, after about 40 µs, we can achieve a higher efficiency by deliberately turning on a perpendicular magnetic field (e.g. the blue curve at 161 mG) than by minimizing stray magnetic fields as good as we can (violet curve). Another important observation is that the width of the revival peaks scales inversely with the strength of the magnetic field, from which we can extrapolate that we can only minimize the magnetic field to ~ 3 mG (violet curve). The remaining magnetic field effectively shortens the achievable storage time, as the next peak comes long after other effects already cause the efficiency to fall to zero (this is described with lifetime τ, which we measure in the second part of the experiment and show in Fig. 6).

3.2 Polarized atoms

We have demonstrated that deliberately turning on a magnetic field is beneficial to our quantum memory. However, the collapses between the peaks do not enable us to recall the stored light at any given time. This could in principle be solved by dynamically adjusting the strength of the magnetic field to the desired time of the revivals. However, the execution of such an experiment would be quite difficult, and a more elegant solution can be achieved by polarizing the atoms.

Along with the control and signal beams, we can also shine a strong polarizing beam on the atoms. By turning on the polarizing beam with σ^+ polarization and a magnetic field $B \sim 100$ mG in the direction parallel to the signal beam, we can polarize about 80 %

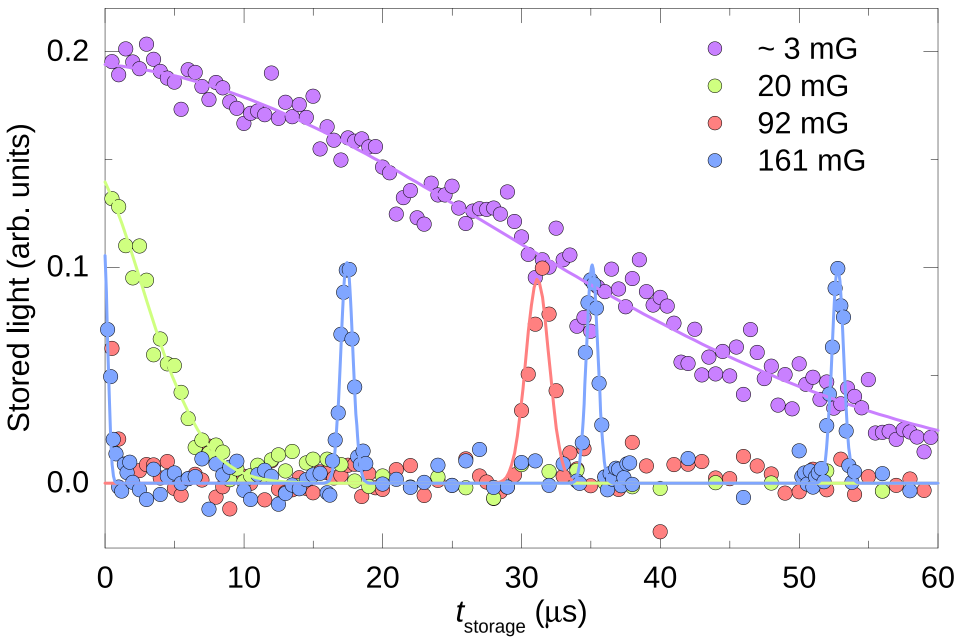

Figure 5: Storage efficiency with non-polarized atoms in different magnetic fields. Spin waves from different m_F sublevels interfere and create a periodic pattern in the amplitude of the retrieved light as a function of storage time. The frequency of the occurrence of the revivals is proportional to the magnetic field strength. In a very small magnetic field (3 mG, violet) this occurs as an effective shortening of the memory lifetime. For a higher magnetic field (161 mG, blue) we achieve a higher efficiency at the peak of a revival than at the lowest achievable magnetic field.

of atoms into the $|F = 3, m_F = 3\rangle$ Zeeman sublevel. The magnetic field determines the quantization axis.

For this part of the experiment, all three beams are σ^+ polarized and the separation of the control beam and the signal beam is only spatial, as shown on Fig. 4. Due to this kind of polarization, we can simplify Eq. 1. The only possible transitions in this case are those with $n = m$, as shown in Fig. 3, so the double sum reduces to a sum over the magnetic sublevels of $|F = 3\rangle$ and $P_{n,m}$ reduces to $P_{n,n} = p_n$. The simplified equation takes the form

$$A(t) = A(0) \left| \sum_{n=-3}^{3} p_n e^{i(\omega_0 + 2n\omega_L)t} \right|^2 e^{-t/\tau}. \tag{2}$$

We see that, in this case, the revivals occur every half Larmor period and not only every Larmor period as in the previous section.

Because the atoms are polarized, fewer magnetic sublevels contribute to the quantum memory and, consequently, fewer spin-waves with different frequencies are formed. If we assume that the atoms occupy only sublevels $m_F = 2$ and $m_F = 3$ (which turns out to be an accurate assumption for our experiment), Eq. 2 simplifies to

$$A(t) = A(0) \left[p_3^2 + p_2^2 + 2p_2p_3 \cos(2\omega_L t) \right] e^{-t/\tau}. \tag{3}$$

We can see that, for $p_2, p_3 \neq 0$, the efficiency then oscillates as a simple cosine function and never reaches zero (except for the special case $p_2 = p_3 = 1/2$). This prediction agrees with our experimental results, shown in Fig. 6. In Fig. 6a, we compare the efficiency of our quantum memory with non-polarized and polarized atoms. It is obvious that polarizing the atoms increases our overall efficiency, as well as making sure that the efficiency does not fall to zero during the collapses. In Fig. 6b, we show a measurement of retrieved light efficiency with polarized atoms up to 400 µs. The efficiency never reaches zero, and the calculated lifetime τ is $\sim$ 300 µs.

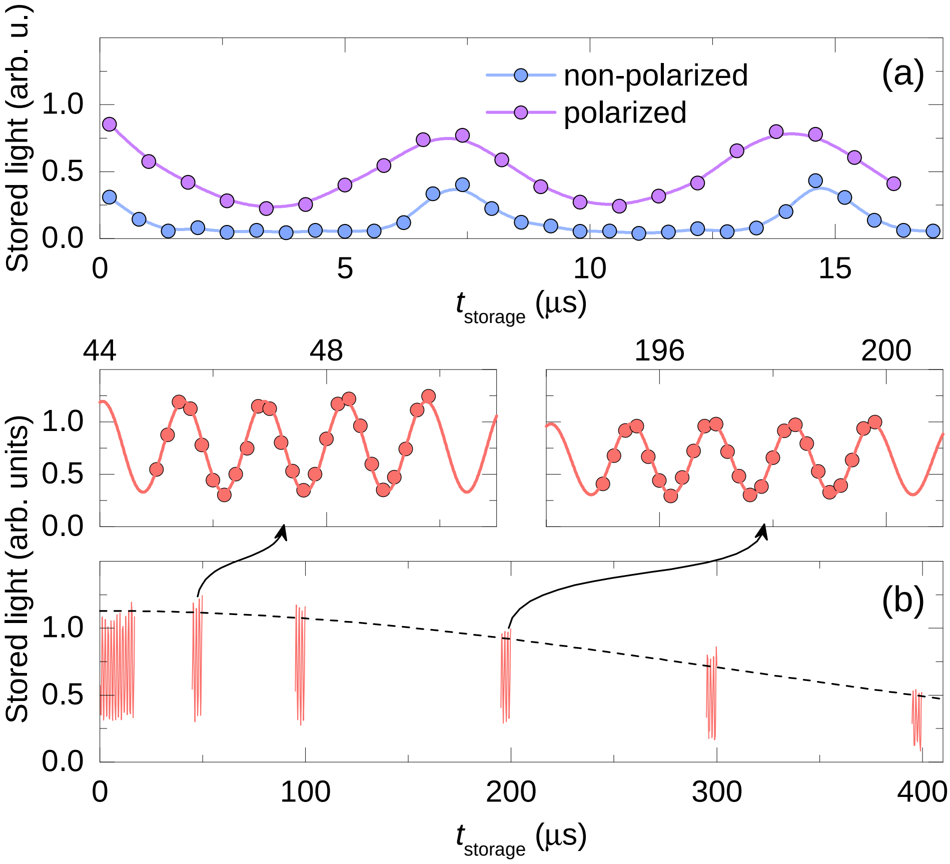

Figure 6: Polarization of atoms and the lifetime of revivals. (a) Stored light as a function of storage time in a similar magnetic field with and without using a polarizing beam to polarize atoms. (b) With polarized atoms in an applied magnetic field, we measured the lifetime of the quantum memory of 300 µs and without efficiency falling to zero for any storage time.

4 Conclusion and outlook

Completely annulling magnetic fields in cold atom experiments is very difficult. Due to the interference of many spin-waves with different energies that get excited when running an EIT-based quantum memory experiment in a weak magnetic field, the achievable lifetime of the quantum memory is significantly shortened.

We have shown that deliberately turning on a magnetic field instead enables us to achieve much longer storage times. However, the collapses of the stored light amplitude discretize such a quantum memory.

A possible application of these collapses and an interesting research direction in the future is temporal multiplexing of the quantum memory [29]. In principle, one could send two signal pulses into the same atomic cloud and read the signals at the time of the corresponding revival for each input pulse separately. Here, the complete collapse of the dark-state polariton would ensure that the output pulse would consist of purely the corresponding input, since the other input is completely suppressed.

For a typical quantum memory experiment, however, a continuous storage is desired. We have demonstrated that polarizing the atoms reduces the collapses, so that the efficiency does not fall to zero between revival peaks. This, along with turning on a strong magnetic field, enables us a tenfold increase in continuous storage time, up to 400 μs.

The depth of the collapses could further be reduced by having an even stronger magnetic field. In this case, one could make use of the large Zeeman splitting by detuning the control beam towards the outermost magnetic sublevel, or even slightly over it. With this kind of frequency selectivity, the probability for spin-waves with different energies to form would be much smaller, which would lead to less interference and shallower collapses.

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