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Quantum Memory with Hot Cesium Atoms

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Abstract

Quantum memory (QM) is a subject of increased scientific and technological interest due to the accelerated development of quantum networks and quantum computing. Electromagnetically induced transparency (EIT) conducted on hot atoms offers a technologically relatively simple implementation of quantum memory, thus being very promising for future scalability and mass production. This seminar focuses on the theoretical background of EIT based QM and its application to our ongoing research at Laboratory for cold atoms at Jožef Stefan Institute. In our experiment we study EIT in a cesium vapor at room temperature, where the ground, excited, and storage states of cesium atoms form a three-level Λ system. We have so far successfully demonstrated storage of light for few μs. We are exploring various parameters (e. g. buffer gas pressure, temperature, magnetic field, polarization, etc.) in order to improve our QM's storage time.

1 Introduction: Why do we need quantum memory?

In quantum computing, a **qubit** (abbreviation of quantum bit) is a basic unit of quantum information. A qubit is a two-state quantum-mechanical system. Two good examples are the spin of the electron in which the two levels can be taken as spin up and spin down; or the polarization of a single photon in which the two spin states (left-handed and the right-handed circular polarization) can also be measured as horizontal and vertical linear polarization [1, 2].

Quantum communication is the exchange of qubits between multiple participants. A practical application of this is quantum cryptography. The most well-known security protocol in quantum cryptography is quantum key distribution (QKD). It enables two parties to produce a shared random secret key known only to them. This key can then be used with any chosen encryption algorithm to encrypt (and decrypt) a message, which can then be transmitted over a standard communication channel. If a hypothetical third party attempts to intercept the quantum information, they would perform a quantum measurement, causing the wave function carrying the information to collapse. Communicating parties would recognize this as a significant enough difference between the sent and received information, adjusting the encryption key exchange accordingly, thus keeping communication ultimately safe [3, 4] Consequently, quantum communications are exceptionally secure compared to classical methods, and significant investments are being made worldwide in their development. Since early 2000's up until now there have been multiple implementations realized in Europe, USA and Asia [4].

However, quantum communication is no exception to (omnipresent) attenuation, hence losses due to photon absorption within optical fibers and quantum decoherence allow reliable transmission only over limited distances [5]. For arbitrarily long distances, intermediate stations, known as trusted nodes, are necessary to split these distances into short enough segments on which QKD still works well. At these points, quantum information is, due to current technology limitations, temporarily converted into classical information, which represents a weak point in the communication line. This issue could be solved with quantum repeaters. Unlike trusted nodes, these devices store qubits, maintaining the quantum nature of information at all times. An essential component of quantum repeater is therefore a **quantum memory**, a device that can temporarily store quantum states and retrieve them at later time, which finally brings us to our topic.

2 Quantum memory

2.1 Definition

Quantum memory is a device that enables the storage of quantum information and its later retrieval (See Figure 1). An informational qubit is prepared using a particle with two distinct quantum states. The main challenge in building such a device is the collapse of the wave function after measurement is made, hence no measurements can be performed on the qubit itself. Instead, its information must be directly transferred to matter using specific physical phenomena [6, 7]. With this in mind, let us now take a detailed look into what quantum memories should be, could be, and what they currently are.

2.2 Requirements

There are many different approaches to quantum memory implementation, therefore there is a need for a system of standard parameters, through which we can then compare this different approaches. The following parameters are the main assessment criteria of a quantum memory:

- **Fidelity** (F) quantifies how closely the retrieved quantum state matches the input state. It can be a good measure of *how quantum* a memory really is [8].
- **Efficiency** (η) represents the energy ratio between retrieved and input states. To minimize additional transmission losses, efficiency should approach 100%.
- **Memory time** (τ) - or storage time - refers to the duration over which a quantum state remains faithfully stored, with decoherence limiting storage time and affecting both fidelity and efficiency. In practical quantum communication schemes, memory times ranging from tens of milliseconds to a few seconds are required, depending on the protocol and the length of the communication link.

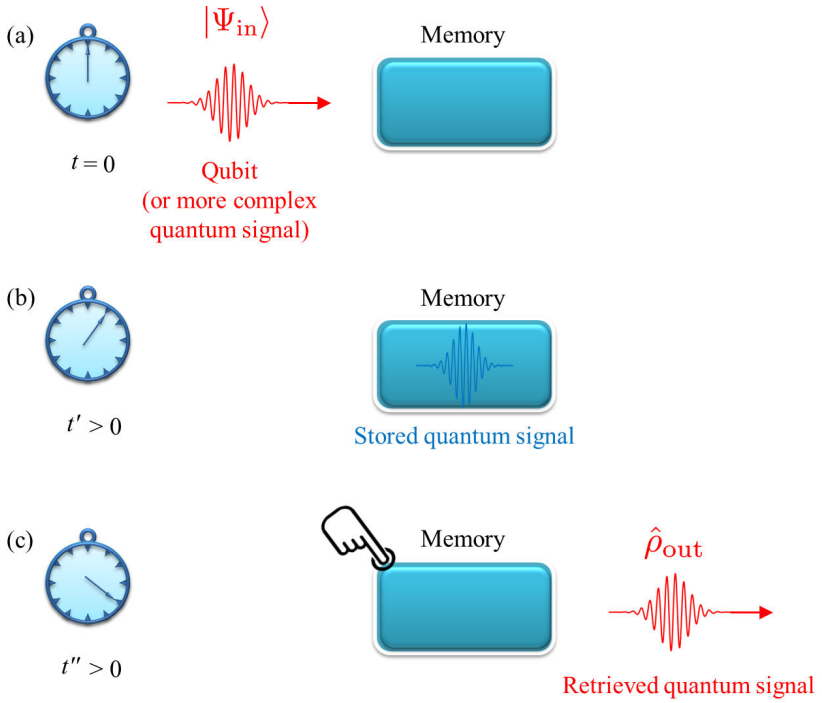

Figure 1: **General concept of a quantum memory**. (a) At time $t = 0$, a qubit arrives at the memory into which it is transferred. (b) The qubit remains stored in the memory for an arbitrary time. (c) At a later time t'', when the user "pushes a button", the quantum state is released out of the memory. If the storage time t'' exceeds the memory lifetime τ, then parameters of QM start to deteriorate. Adapted from [6].

- **Multimode capacity** denotes the number of elementary quantum states a memory can store in parallel, enhancing the speed and efficiency of quantum communication protocols.
- **Wavelength** of fiber-optics quantum communications. Memories should ideally operate at telecom wavelengths ($\lambda = 1.3$ to $1.5\,\mu$m), though quantum interfaces can convert photons between telecom and visible wavelengths.
- **Bandwidth** of quantum memory. It describes spectral width of photons that a quantum memory is able to store. In general wider bandwidths are desired, but in practice they are always limited depending on different QM approaches.
- **Signal-to-noise ratio** - Quantum memories often use auxiliary bright beams alongside single-photon signals, requiring strict noise suppression to preserve the quantum nature of the signal. Excess noise can obscure the "*quantumness*" of stored information [6].

Individual QM systems are usually optimized for a few of these parameters, but presently there are none, that can simultaneously optimize all of them. From here on, we will mainly focus on **storage time** parameter, since this parameter is currently the limiting factor of most of QM implementations.

2.3 Quantum memory protocols

Before focusing on the one of most promising mechanisms – electromagnetically induced transparency (EIT), let us first list different types of QM approaches that are currently being investigated.

The first and simplest idea for QM would of course be long enough fiber loop, where an incoming photon is redirected into the delay loop using a switch and is later released. However, this approach does not yield sufficient efficiency, mostly due to reflection and transmission losses of the various optical components [9].

Quantum memories can be roughly categorized into two main types: single quantum emitter-based and ensemble-based approaches. These categories differ in the physical substrates used for storing quantum information and the protocols that enable the mapping of quantum states onto these substrates [6].

Single quantum emitter-based memories store information in isolated quantum systems. These systems are ideal for fundamental quantum experiments and specific applications like high-fidelity qubit storage and long-distance entanglement. Existing protocols are:

- **Single atoms in cavities:** Optically trapped single atoms in cavities have been used to demonstrate the storage of polarization qubits [10] and the generation of matter-matter entanglement.
- **Individual trapped ions:** Individually addressable ions exhibit long coherence times and enable qubit teleportation and photon-to-ion state mapping with 95% fidelity but low efficiency [11].
- **Nitrogen-vacancy centers in diamonds:** Nitrogen-vacancy centers (NVC) are naturally occuring or engineered defects in bulk diamond exhibiting rich quantum properties. They enable photon-spin entanglement, state transfer to nuclear spins with millisecond coherence times, and long-distance entanglement between NVCs. Disadvantageous for these applications is the long radiative lifetime of the NVC and the strong phonon sideband in its emission spectrum [12].
- **Quantum dots:** They are semiconductor particles (a few nanometres in size) with optical and electronic properties that differ from those of larger particles due to quantum mechanical effects. They are being studied as potential QM systems [13].

Ensemble-based memories use collective properties of many particles to store quantum states. These systems support multimode storage and offer a variety of very different protocols:

- **Cold or ultra-cold atomic gases:** They were earliest media used for light storage. Very pure gases of alkali atoms are prepared via laser cooling at various temperatures, from a few mK in magneto-optical traps to μK in dipole traps and even in the nK range in Bose-Einstein condensates (BEC). This protocol also constitutes the main research interest at Laboratory for cold atoms (IJS), where storage time of more than 400 μs was achieved using magneto-optical trap [14].
- **Hot atomic vapors:** Here hot refers to temperature range above 300 K, which mostly implies room temperature gases, which enable EIT and Raman-based protocols, showing quantum behavior in optical storage experiments despite higher temperatures. This type of QM is much easier to implement, since there is no need for laser cooling. It represents main topic of interest of this seminar.
- **Rare-earth-doped crystals:** These materials can experience extremely long coherence times at cryogenic temperatures. They are therefore studied as versatile light storage media. EIT-based light storage in a crystal has been shown, shortly after it was performed on atomic vapors.
- **Microcavity coupled NVC ensembles:** Theoretical proposal suggests that NV centers in diamond could also be used as a medium for an ensemble-based memory [6].

2.4 Decoherence

Decoherence, the loss of quantum coherence, is the primary obstacle for quantum memories and quantum information systems. It is the phenomenon that primarily limits storage times. While eigenstates of observables are relatively stable, superpositions of such states are fragile due to phase blurring over time. This process transforms pure quantum states into classical (non-quantum) mixture states, rendering them useless for quantum purposes. Overcoming decoherence and controlling its sources is a critical focus in quantum memory research. Despite its challenges, research is showing promising indications of finding systems where quantum states can persist for extended durations [15].

In our case, when considering ensemble-based memories, inhomogeneities will cause different atoms (at different positions or with different velocities) to evolve with uncorrelated individual phase factors. Since the re-emission process happens as a collective in-phase emission from all the atoms, an uncontrolled dephasing will oppose to this desirable collective re-emission. [7, 6]

From our own lab experiences we can state, that overcoming decoherence and controlling its sources is a crucial challenge in quantum memory research. In hot atoms QM, we try to reduce it by adding

the right amount of buffer gas to the cells and so limit the motion of atoms. In some cases the choice of coating of the cell walls also plays a role as it affects interactions of atoms with the cell walls during collisions. Most commonly used substances are paraffin or alkene coating.

3 Electromagnetically induced transparency

One of the most promising mechanisms for quantum memory implementation is electromagnetically induced transparency (EIT). As name suggests it occurs in some media when a light beam that should normally be absorbed, is instead transmitted. Light propagating in an EIT medium experiences an extremely reduced group velocity. To store a light pulse using EIT, its group velocity is adiabadically reduced to zero while it propagates inside the medium. This process transfers the quantum state of the light pulse into an atomic coherence [6]. EIT is the destructive quantum interference of two light fields in a three-level atomic energy structure. There are three possible configurations for a three-level structure known as lambda (Λ), vee (V) and ladder, respectively, as shown in Figure 2. We will focus only on the lambda configuration, as it is the one most commonly used for implementing quantum memory and is also the one we are using with ^{133}Cs in our experiment (see Chapter 4.1).

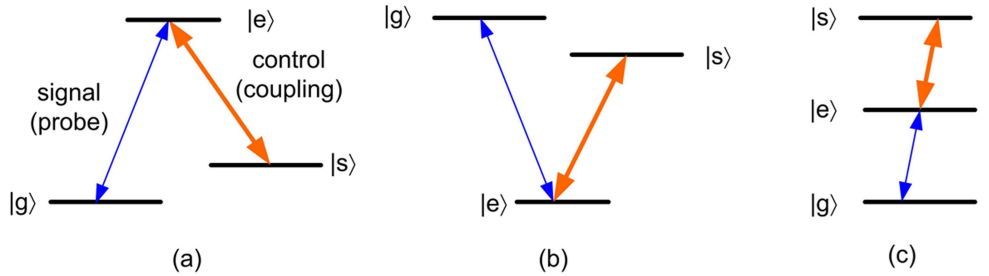

Figure 2: Three possible configuration of EIT, (a) lambda, (b) vee and (c) ladder. Adapted from [7].

Let us take a closer look at energy level description of this phenomena. We will name three levels that form a Λ system: **ground** $|g\rangle$, **excited** $|e\rangle$, and **storage** $|s\rangle$. The atomic ensemble is illuminated with two lasers: a weak signal (also called *probe*) beam with a wavelength corresponding to the transition between $|g\rangle$ and $|e\rangle$, and a strong control (also called *coupling* or *pump*) beam corresponding to the transition between $|e\rangle$ and $|s\rangle$.

In the Λ configuration, the transition between the two lower energy states, $|g\rangle$ and $|s\rangle$, is dipole-forbidden, allowing atoms to remain in these states for extended periods. Both states have allowed transitions to an excited state, $|e\rangle$. To modify the propagation of a signal beam coupling $|g\rangle$ and $|e\rangle$, a strong control beam is applied between $|s\rangle$ and $|e\rangle$. Each field is resonant with the respective atomic transitions and is absorbed when applied individually. However, when both beams are present, they quantumly interfere destructively, preventing excitation to $|e\rangle$, and thus neither beam is absorbed [7]. Essentially, this is a two-photon process from $|g\rangle$ to $|s\rangle$ via $|e\rangle$).

When we want to retrieve the photon, we turn the control beam back on, and the atom transitions from the state $|s\rangle$ via $|e\rangle$ to the ground state, emitting a photon with the same energy as the signal photon, which we proclaim as stored light. Although this explanation is intuitive and explains how energy of photon is conserved it does not explain how quantum information of photons (that is polarization etc.) is copied onto atom ensemble [6, 16].

3.1 Slow light

Let us now try to understand, how light is actually slowed.

From complex refractive index $n = n' + in''$, using the Kramers-Kronig relations, we obtain the real part of refractive index [7] as

$$n' = 1 + \frac{1}{2}\mathrm{Re}\chi(\omega), \tag{1}$$

indicating that the real part of the electric susceptibility, $\chi(\omega)$, determines the refractive and reflective properties of light. Additionally, the imaginary part of the susceptibility is proportional to the absorption

in the medium, thus merely increasing the refractive index cannot significantly slow down light, as higher values of n cause substantial absorption. However, there exists a special regime where this issue can be circumvented: we prepare the same configuration as in the previous section (a three-level Λ energy configuration illuminated by two beams). Intuitively, absorption in the medium can occur when only one beam is active, but when both beams are active simultaneously, no atom can be in the excited state $|e\rangle$. As a result, light cannot be absorbed, and the medium becomes transparent. This phenomenon can be described quantitatively through the expression for the linear susceptibility when the control beam is strong and its intensity is constant. By combining the Kramers-Kronig relations with the theory of Rabi oscillations and dressed states, derivation [6, 7] yields

$$\chi(\omega) = g^2 N \frac{\gamma_{gs} + i\omega}{(\gamma_{ge} + i\omega)(\gamma_{gs} + i\omega) + |\Omega|^2}, \tag{2}$$

where γ_{gs} and γ_{ge} are the decoherence rates for the transitions $|g\rangle \to |s\rangle$ and $|g\rangle \to |e\rangle$ respectively, where in our case $\gamma_{gs} \to 0$, due to forbidden transition between these states. g is the atom-field coupling constant (which is dependent only on properties of atomic energy levels and independent of light properties), N is the number of atoms in the ensemble, Ω is the Rabi frequency of the control beam (with $|\Omega|^2$ proportional to the control beam intensity), and ω is the frequency detuning between the signal and control beam resonance (in resonance holds $\omega = 0$) [6, 7, 16]. Figure 3 shows the graphs of the real and imaginary components of the susceptibility obtained from Equation 2.

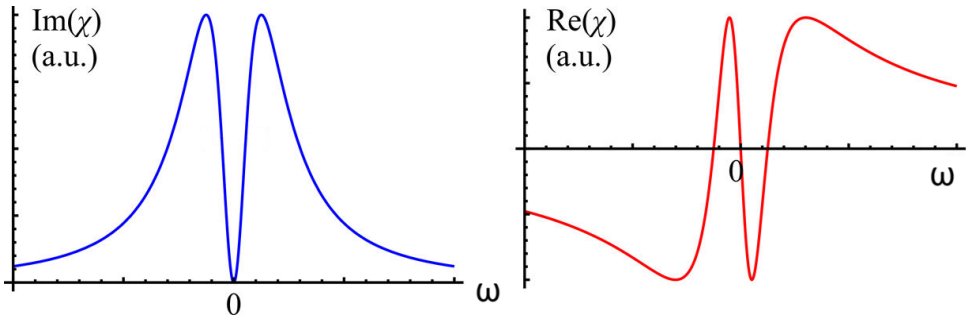

Figure 3: Linear susceptibility spectrum (in arbitrary units) of the EIT medium ($\gamma_{gs} \to 0$) for a signal beam. Real part of the susceptibility characterizes refractive properties and imaginary part characterizes absorption. Adapted from [6].

We observe that $\omega = 0$ corresponds to the zero value of the imaginary part of $\chi(\omega)$, which means that a narrow window of transparency appears, where light is not absorbed. In the same interval, the refractive index n' (see Equation 1) has a very steep frequency dependence. Let us now recall the equations for the phase velocity of the wave (the speed of propagation of wavefronts) and for the group velocity of the wave (the speed of propagation of wave packets) [17]

$$v_{\mathrm{p}} = \frac{\omega}{k} = \frac{c}{n'}, \tag{3}$$

$$v_{\mathrm{g}} = \frac{\partial \omega}{\partial k} = \frac{c}{n' + \omega \frac{\partial n'}{\partial \omega}} \tag{4}$$

where c is the speed of light in vacuum, n is the refractive index and ω is the frequency of light. If the refractive index does not change with frequency, the two velocities are the same. When the refractive index changes with respect to the frequency, then the group velocity will be smaller than phase velocity. In the case of a very steep change, the group velocity will be greatly reduced. We note that in the narrow window around $\omega = 0$ the group velocity can become significantly smaller than c, due to the steep frequency dependence of the refractive index in the denominator. As we have seen, $n'(\omega)$ is very steep in this range. Let us now evaluate derivative $\frac{\partial n'}{\partial \omega}$ from Equations (1) and (2) and plug it in Equation 4 along with n' evaluated from (Equation 1). This gives us

$$v_g = \frac{c}{1 + g^2 N/|\Omega|^2}, \tag{5}$$

which clearly states, that group velocity is dependent on the atomic density and control beam intensity. Increasing the atomic density or decreasing control beam intensity will reduce the group velocity of the signal beam. This has been demonstrated theoretically and practically (also in our lab). Said phenomenon is called the **slow light**. In practice, the most spectacular experimental demonstration of this ultra slow light effect was done by Hau et al. [18] in 1999. They measured a signal group velocity of 17 ms^{-1} in a Bose-Einstein condensate of sodium atoms [16].

3.2 Stored light: Dark-state polariton description

Even if we significantly reduce the speed of light, we still cannot store it. Moreover, we still lack an answer to the question of how an EIT medium could preserve the full quantum state of a photon, rather than merely satisfying the energy picture! It turns out that an adiabatic change in the intensity of the control beam can influence the dynamics of the signal beam with minimal losses. Furthermore, if we quickly switch off the control beam, the group velocity of the signal pulse is reduced to zero, effectively storing it in the EIT medium until it is retrieved by turning the control beam back on [16]. The reduction in group velocity is also evident from Equation (5): when we set $|\Omega| \to 0$, then $v_g \to 0$.

To explain this phenomenon, we use the theory of so-called *dark-state polaritons* [19, 20]. The *dark-state polariton* is a quasiparticle, a superposition of electromagnetic waves and atomic excitations. Its quantum state $\Psi(z,t)$ is a superposition of the photonic component $E(z,t)$ and the spin component $S(z,t)$

$$\Psi(z,t) = \cos\theta E(z,t) + \sin\theta S(z,t), \tag{6}$$

where

$$\cos\theta = \frac{\Omega}{\sqrt{\Omega^2 + g^2 N}}, \quad \sin\theta = \frac{g\sqrt{N}}{\sqrt{\Omega^2 + g^2 N}}. \tag{7}$$

Equations (6) and (7) follow from solving the Heisenberg-Langevin equations (done in [19]), which exceeds the scope of this seminar. Therefore we will settle with the understanding of said expressions.

After the signal pulse enters the EIT medium and the control beam is turned off ($\Omega \to 0$), the photonic component is reduced to 0, hence leaving Ψ to consist only of spin component. When the control beam is turned back on, the signal is "read out" and found to be in the same quantum state as it was initially.

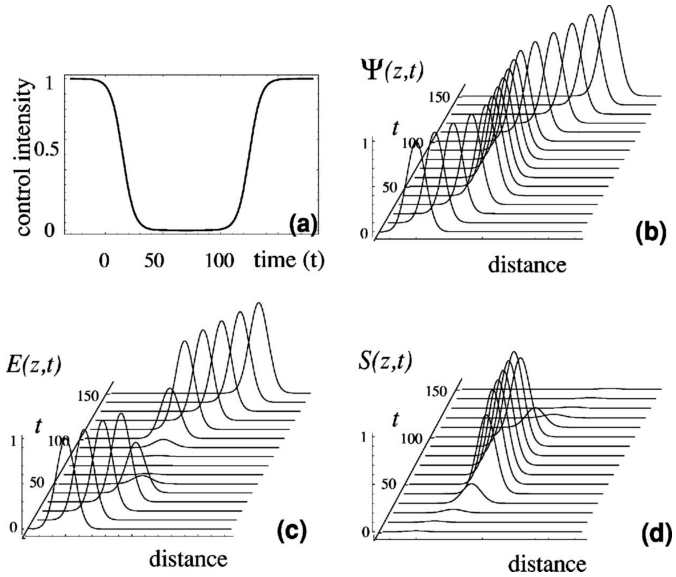

Figure 4: Graphic representation of the process of storing light. The photonic and spin parts of the dark state polariton during the passage through the EIT medium under the influence of the control beam. In the individual panels: a) temporal dependence of the control beam intensity, b) temporal and spatial dependence of the entire Ψ, c) temporal and spatial dependence of the electromagnetic component, d) temporal and spatial dependence of the spin component. Adapted form [20].

Figure 4 shows graphic representation of this process. With the control beam turned off (time interval 0–50), the wave function moves only along the temporal dimension. At the same time, we note how the photonic component drops to 0, while the spin component reaches its maximum value.

Around time 100 (Fig. 4 (c)), we observe the opposite phenomenon: the wave function moves again along the temporal dimension, while the spin component drops to zero and the electromagnetic component reaches its maximum value. It is graphically evident that Fig. 4 (b) is the sum of Fig. 4 (c) and Fig. 4 (d) as written by Equation (6).

Although much more could be said about theoretical background of EIT, this suffices to understand the general theoretic ideas behind this phenomena, so we can move on to our particular experimental research conducted at Laboratory for cold atoms at Jožef Stefan Institute.

4 Quantum memory with hot Cs atoms at Laboratory for cold atoms, IJS

4.1 Hyperfine structure of cesium atom

Cesium is an alkali metal, meaning it has only one valence electron. Its sole stable isotope is ^{133}Cs. The angular momentum of an atom is the sum of the electron spin $\mathbf{S}$, the electron orbital angular momentum $\mathbf{L}$ and the nuclear angular momentum $\mathbf{I}$. The energy levels of an atom are primarily determined by the quantum number associated with the electron orbital angular momentum $\mathbf{L}$. These levels are further split into the fine structure due to spin-orbit coupling, described by the total electron angular momentum $\mathbf{J} = \mathbf{L} + \mathbf{S}$. An additional splitting, known as the hyperfine structure, arises from the coupling of $\mathbf{J}$ with the nuclear angular momentum $\mathbf{I}$, resulting in the total atomic angular momentum $\mathbf{F} = \mathbf{J} + \mathbf{I}$. [21, 22]

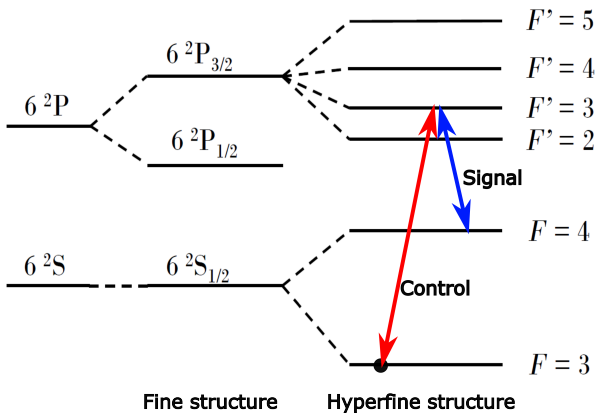

Figure 5: Energy levels of the ground and first excited state of ^{133}Cs atoms with control and signal transitions drawn. The energy splittings are not to scale, but Λ system theoretically discussed in Chapter 3 is clearly visible. (It is worth mentioning that $|6P_{1/2}\rangle$ also splits into two hyperfine levels, which are not depicted due to clarity of QM relevant levels.) Adapted from [21].

In the cesium ground state, the valence electron occupies an orbital with $L = 0$ and has a spin $S = \frac{1}{2}$, leading to a total electron angular momentum of $J = \frac{1}{2}$. Since the nuclear angular momentum of cesium is $I = \frac{7}{2}$, the hyperfine structure splits the ground state into levels with $F = 4$ and $F = 3$, where the latter has lower energy. The energy level structure of the ground state and the first excited state of a cesium atom is illustrated in Figure 5. For our QM's Λ-system, we choose the following ^{133}Cs hyperfine structure levels: $|g\rangle = |6S_{1/2}, F = 3\rangle$, $|s\rangle = |6S_{1/2}, F = 4\rangle$, and $|e\rangle = |6P_{3/2}, F' = 3\rangle$. Precise data on these levels, chosen for control and signal transitions, is obtained from [23].

4.2 Optical setup

First we need to prepare the signal and control beams to precisely match wavelengths corresponding to $|g\rangle \rightarrow |e\rangle$ and $|s\rangle \rightarrow |e\rangle$ level transitions respectively. We prepare them on separate optical table with

suitable double-pass optical systems using acousto-optic modulators (AOM's) [24]. These beams are then coupled into optical fibers and transported to another optical table where the hot QM experiment is being conducted. The optical setup we built is schematically presented in Figure 6. From optical fibers, we obtain linearly polarized signal and control beams. Using $\lambda/2$ wave plates, we polarize the first beam horizontally and the second vertically. The control beam is then expanded using two lenses. Both beams are coincided at a polarizing beam splitter (PBS) and then circularly polarized using a $\lambda/4$ wave plate - one σ^+, the other σ^-. The beams are then sent through a cesium cell located within triple μ-metal shields, which isolates the system from Earth's magnetic field. Inside μ-metal shields are mounted 3 nested orthogonal Helmholtz coils centered on Cs cell, which can precisely generate a magnetic field, if we are doing lifetime measurements in magnetic field. At the exit of the chamber, the beams are linearly polarized back again, and the control beam is filtered out using a Glan-Thompson polarizer, so that only the retrieved signal beam is measured with a photodiode at the end of optical line.

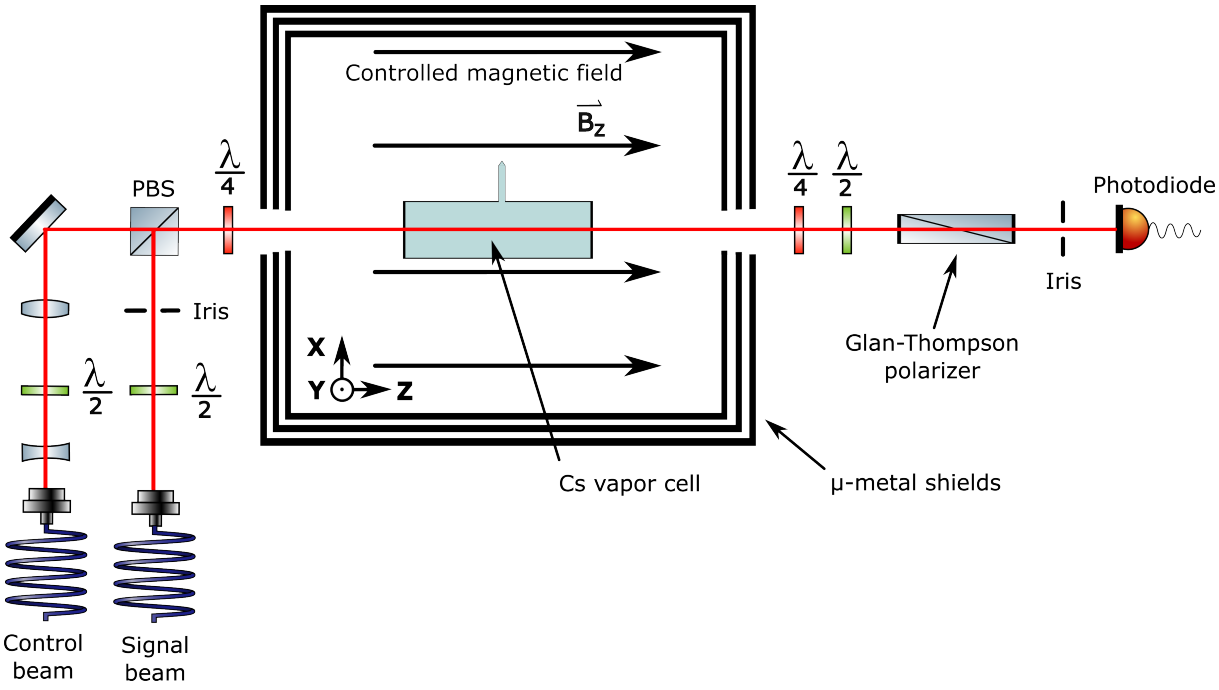

Figure 6: Setup of hot Cs atoms quantum memory experiment at Laboratory for cold atoms.

The time sequence of beams we illuminate Cs atoms with is depicted in Figure 7. It is important to note that we do not work with single photons, but with classical light pulses. AOM's which in the end control beams are controlled by software written in `python`. Read signal is after detection numerically integrated in `MATLAB` and the result assigned as stored light to given storage time, that we were measuring. We fully automated this process, allowing us to be able to relatively easy change different parameters and repeat measurements. We measure the influence of magnetic field, partial pressure of buffer gas and other potentially interesting parameters on the performance of our QM. Figure 8 shows set of measurements, measuring lifetime of our QM under different magnetic fields, where interesting periodic features can be observed. The frequency of such periodic *revivals* and *collapses* of the stored light is proportional to the magnetic flux density. Although very interesting, effects of magnetic field on our QM will not be further discussed in this seminar, since they fall out of its limited scope.

5 State of the art

The field of hot atoms QM is developing at rapid pace, due to increased technological interest. Some of the best achievements of the field are a room-temperature quantum memory using warm rubidium vapor that performs a high-fidelity retrieval (95%) at storage time of **160 μs for single-photon operations** and up to **1 ms for classical-level light** by suppressing atomic diffusion [25]. Another significant achievement of research group from Weizmann Institute of Science was a record **1 second** storage time

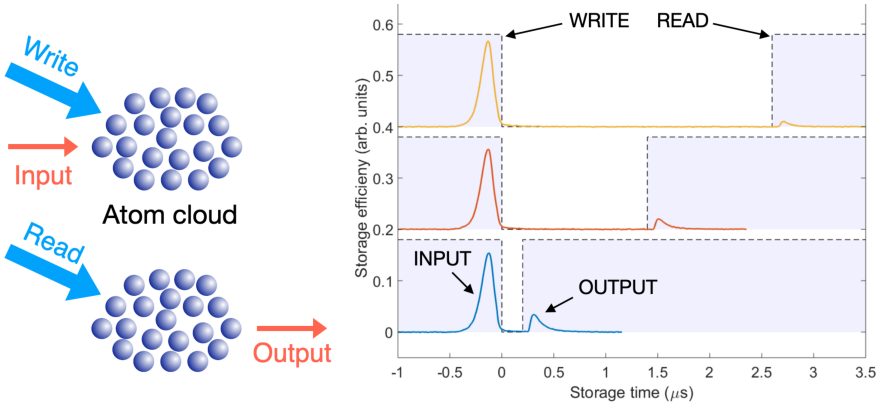

Figure 7: Graphics on left schematically depicts our acting on atom ensemble, while the right graphs show signal sequences performed with three different choices of control (dashed line) OFF time i.e. storage time. Courtesy of Dr. Jeglič.

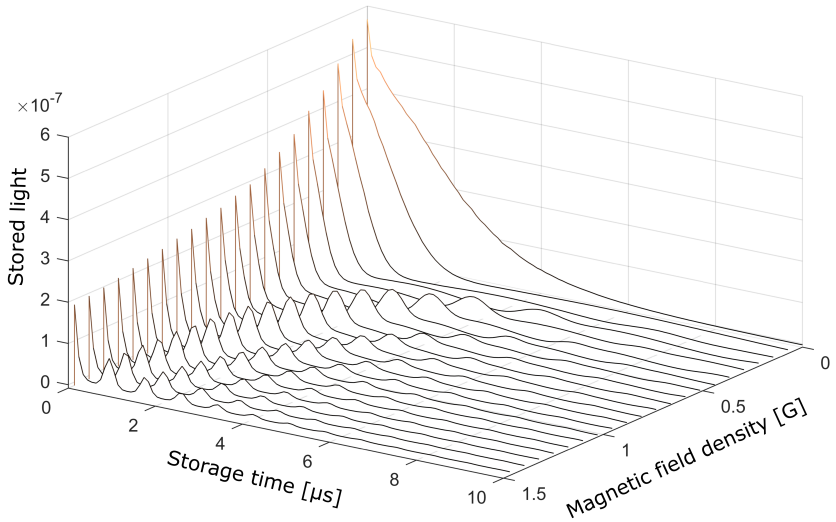

Figure 8: When doing lifetime measurement of our QM under different magnetic fields interesting periodic features can be observed. The frequency of such periodic *revivals* and *collapses* of the stored light is proportional to the magnetic flux density [14].

QM on room temperature Cs vapor, achieved by exploiting a decoherence-free subspace, overcoming spin-exchange collision limitations and surpassing previous techniques by two orders of magnitude [26]. These developments set new benchmarks for storage times and scalability, paving the way for more robust and deployable quantum memories.

6 Conclusion

The aim of this seminar was to inform reader on reasons why quantum memory is becoming increasingly researched topic. The overview of the quantum memory requirements and properties has been made as well as the overlook of different developing and emerging protocols for it. We focused on electromagnetically induced transparency and explained its theoretical background from three different angles of perspective, which complement each other. It has been explained why it is difficult to store light successfully for arbitrary durations and how this is practically performed, including concrete explanation of research work being done in this field by Laboratory for cold atoms at Jožef Stefan Institute. Among their achievements in field of quantum memory are successful demonstration of slowing and storing of

light in both cold Cs atoms in magneto-optical trap (MOT) (storage times of more than 400 μs [14]) and hot Cs atoms (best currently achieved storage times of 5 μs). State of the art research instills hope, that this results can be greatly improved in future, which is also the main objective of our future endeavours.

Acknowledgements

As topic of this seminar is motivated and inseparably connected to research work conducted at Laboratory for cold atoms within the Department of Condensed Matter Physics (F5) of Jožef Stefan Institute in Ljubljana, I cannot conclude without acknowledging all the people involved. Firstly I would like to acknowledge my colleague and coworker **Bor Luka Urlep**, who contributes equally to this experiment. Then I would like to thank to PhD students **Katja Gosar** and **Jure Pirman**, who work on their projects in same laboratory and often provide insightful advice or help out with difficulties we run into. Last but definitely not least I would like to express my sincere gratitude to the Head of the Laboratory for cold atoms **Peter Jeglič**, who makes all this research possible and is always gracefully available to direct us with his vast expertise.

References

[1] A. Ramšak, *Kvantna mehanika*, Fizika : zbirka fizikalnih učbenikov in monografij (Založba Univerze, Ljubljana, 2021).

[2] Wikipedia, *Qubit*, https://en.wikipedia.org/wiki/Qubit [Online; accessed 22-December-2024].

[3] R. Singh and R. M. Bodile, *A Quick Guide to Quantum Communication* (arXiv, ePrint, 2024) arXiv:2402.15707 .

[4] Wikipedia, *Quantum network*, https://en.wikipedia.org/wiki/Quantum_network [Online; accessed 22-December-2024].

[5] N. Sangouard, C. Simon, H. de Riedmatten, and N. Gisin, *Quantum repeaters based on atomic ensembles and linear optics*, Rev. Mod. Phys. **83**, 33–80 (2011).

[6] A. Nicolas, *Optical quantum memories with cold atomic ensembles : a free space implementation for multimode storage, or a nanofiber-based one for high collection efficiency*, Ph.D. thesis, Université Pierre et Marie Curie (2014).

[7] L. Ma, O. Slattery, and X. Tang, *Optical quantum memory based on electromagnetically induced transparency*, Journal of Optics **19**, 043001 (2017).

[8] Wikipedia, *Fidelity of quantum states*, https://en.wikipedia.org/wiki/Fidelity_of_quantum_states [Online; accessed 11-December-2024].

[9] T. B. Pittman and J. D. Franson, *Cyclical quantum memory for photonic qubits*, Phys. Rev. A **66**, 062302 (2002).

[10] H. P. Specht, C. Nölleke, A. Reiserer, M. Uphoff, E. Figueroa, S. Ritter, and G. Rempe, *A single-atom quantum memory*, Nature **473**, 190–193 (2011).

[11] C. Kurz, M. Schug, P. Eich, J. Huwer, P. Müller, and J. Eschner, *Experimental protocol for high-fidelity heralded photon-to-atom quantum state transfer*, Nature Communications **5**, 5527 (2014).

[12] Wikipedia, *Nitrogen-vacancy center*, https://en.wikipedia.org/wiki/Nitrogen-vacancy_center [Online; accessed 2-January-2025].

[13] Wikipedia, *Quantum dot*, https://en.wikipedia.org/wiki/Quantum_dot [Online; accessed 21-December-2024].

[14] K. Gosar, V. P. Jevšenak, T. Mežnaršič, S. Beguš, T. Krehlik, D. Ponikvar, E. Zupanič, and P. Jeglič, *Suppression of dark-state polariton collapses in a cold-atom quantum memory*, Phys. Rev. A **108**, 032618 (2023).

[15] Wikipedia, *Quantum decoherence*, https://en.wikipedia.org/wiki/Quantum_decoherence [Online; accessed 12-December-2024].

[16] S. Mattiazzi, Kvantni spomin za fotone, Seminar (2021).

[17] I. Olenik and M. Vilfan, *Optika*, Fizika : zbirka fizikalnih učbenikov in monografij, Vol. 6 (Fakulteta za matematiko in fiziko, Ljubljana, 2023).

[18] L. Hau, S. Harris, Z. Dutton, and C. Behroozi, *Light speed reduction to 17 metres per second in an ultracold atomic gas*, Nature **397**, 594–598 (1999).

[19] M. Fleischhauer and M. D. Lukin, *Dark-state polaritons in electromagnetically induced transparency*, Phys. Rev. Lett. **84**, 5094–5097 (2000).

[20] M. D. Lukin, *Colloquium: Trapping and manipulating photon states in atomic ensembles*, Rev. Mod. Phys. **75**, 457–472 (2003).

[21] K. Gosar, *Single-shot Stern-Gerlach magnetic gradiometer with ultracold cesium atoms*, Matrika **7** (2020).

[22] T. Arh, *Nedestruktivno slikanje in magnetometrija s Faradayevo rotacijo v plinu cezijevih atomov*, Master's thesis, Faculty of Mathematics and Physics, University of Ljubljana (2019).

[23] D. A. Steck, *Cesium D Line data* (revision 2.3.3, 28 May 2024).

[24] M. Čopič, M. Vilfan, and A. Petelin, *Fotonika*, Fizika : zbirka fizikalnih učbenikov in monografij (Fakulteta za matematiko in fiziko, Ljubljana, 2020).

[25] Y. Wang, A. N. Craddock, R. Sekelsky, M. Flament, and M. Namazi, *Field-deployable quantum memory for quantum networking*, Phys. Rev. Appl. **18**, 044058 (2022).

[26] O. Katz and O. Firstenberg, *Light storage for one second in room-temperature alkali vapor*, Nature Communications **9**, 2074 (2018).