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How to measure diffusional decoherence in multimode rubidium vapor memories?

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ABSTRACT

Diffusion is the main limitation of storage time in spatially multimode applications of warm atomic vapors. Precise knowledge of diffusional decoherence in the system is desired for designing most of vapor memory setups. Here we present a novel, efficient and direct method of measuring unbiased diffusional decoherence, clearly distinguished from all other decoherence sources. We found the normalized diffusion coefficients of rubidium atoms in noble gases to be as follows: neon 0.20 cm^2/s, krypton 0.068 cm^2/s and we are the first to give an experimental result for rubidium in xenon: 0.057 cm^2/s. Our method consists in creating, storing and retrieving spatially varying atomic coherence. Raman scattering provides a necessary interface to the atoms that allows for probing many spatial periodicities of atomic coherence concurrently. As opposed to previous experiments the method can be used for any single sealed glass cell and it does not require any setup alterations during the measurements and therefore it is robust and repeatable.

1. Introduction

In recent years warm atomic ensembles have been widely used in many applications in quantum optics and atomic physics. The most promising applications include quantum repeaters [1], quantum memories [2] and ultraprecise magnetometry [3]. They have also been shown to be an effective medium for four-wave mixing processes [4], electromagnetically induced transparency (EIT) [5] and slow light generation [6].

An advantage of using warm atomic gas is undoubtedly simplicity of performing experiments and obtaining large optical depths. However, it entails fast thermal motion of atoms. Atomic motion limits the efficiency of many modern systems that use multimode properties of atomic ensembles. At best this motion can be slowed down and made diffusive by addition of a suitable buffer gas. Since diffusion is usually the main source of decoherence in multimode vapor memory systems, ability to measure and control its speed is highly desired. In particular it would be very useful to distinguish pure diffusional decoherence from other decoherence effects.

There are a number of currently developing systems where diffusion is the main limitation. An important example of such a system is storing and retrieving transverse modes and images in gradient echo memory [7–10], in collective Raman scattering [11] or in EIT [12]. Typically diffusional motion of atoms in a buffer gas limits the storage time [13,14], restricts the number of spatial modes retrieved [11] or broadens the EIT spectrum [15]. Knowledge of the exact diffusion coefficient is particularly important for designing experiments with diffraction cancellation [16,17,12,18]. Further progress would be significantly facilitated if one possessed convenient, robust and repeatable method for precise diagnostic of decoherence in the actual cell of a particular setup.

However, the available methods of measuring diffusion decoherence are indirect and require either variation of buffer gas pressure, prior knowledge of other sources of decoherence [19] or setup alterations within a single measurement [20,21]. This makes them unsuitable for modern experiments where exact knowledge of diffusional decoherence of a single sealed glass cell in a specific setup is required.

Here we propose a novel, direct method which allows us to measure the diffusion in any given cell. The measurement provides more than enough data to verify its self-consistency and single out the diffusion from other motion-independent sources of decoherence. The method should be relatively easy to incorporate into a number of quantum memory setups.

As a demonstration we measure the diffusion coefficients of rubidium in neon, krypton and xenon in sealed glass cells at a pressure of a few torrs. These results will be useful for designing future experiments, since the data available till now is rather scarce and, most importantly, it was retrieved using indirect methods [19,22–28,20]. The data available for neon is inconsistent and that for krypton is hardly available [8,27].

We also recommend using xenon as a buffer gas, for which we provide the very first experimental data as far as we know. Despite

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the latest applications of hyperpolarized xenon [29], the diffusion coefficient of rubidium in this gas has only been deduced from cross sections of velocity changing collisions [30] or interaction potentials [31].

This paper is organized as follows: in Section 2 we introduce the principles of our method, Section 3 describes in detail the experimental implementation, Section 4 contains the experimental results together with the reference data available. Finally, Section 5 concludes the paper.

2. Method

2.1. General idea

Quantification of the diffusive motion of atoms using optical methods can be done in three general steps. At first a group of atoms has to be chosen and distinguished from others by changing their internal state. Then the atoms are let to spread due to diffusion in the absence of light. In the third stage one probes the group and observes the effects of the spread. This general scheme has various implementations [19,22–28,20] which typically consisted in exciting and probing a pencil-shaped atomic group using light beams. Instead here we create and, after a certain delay, probe patterns of spatially dependent atomic coherence $\rho_{01}(\mathbf{r})$ between two long lived atomic levels $|0\rangle$ and $|1\rangle$.

Patterns of atomic coherence are created through spontaneous (Stokes) Raman scattering. Each pattern comprises many plane-wave components with different periodicities. Those components decay at different rates due to diffusive motion of the atoms. After a certain storage time relative contribution of each plane-wave component can be measured by driving the anti-Stokes scattering. Then each plane-wave component acts as a diffraction grating deflecting driving laser beam as illustrated in Fig. 1(a). By measuring the intensity of the anti-Stokes scattering light as a function of deflection angle and time between pattern creation and readout, we can calculate the decay rate of different plane-wave components constituting atomic coherence. We rely on the fact that in the diffusion process periodic patterns of atomic coherence do not change their period but they are blurred over time as depicted in Fig. 1(b). As atoms move, coherence at a specific point $\mathbf{r}_0$ will reshuffle its values with the neighboring points. Evolution of atomic coherence in the dark will be described by the equation of diffusion with a coefficient D and homogeneous depolarization with a rate γ_0 [7,32]:

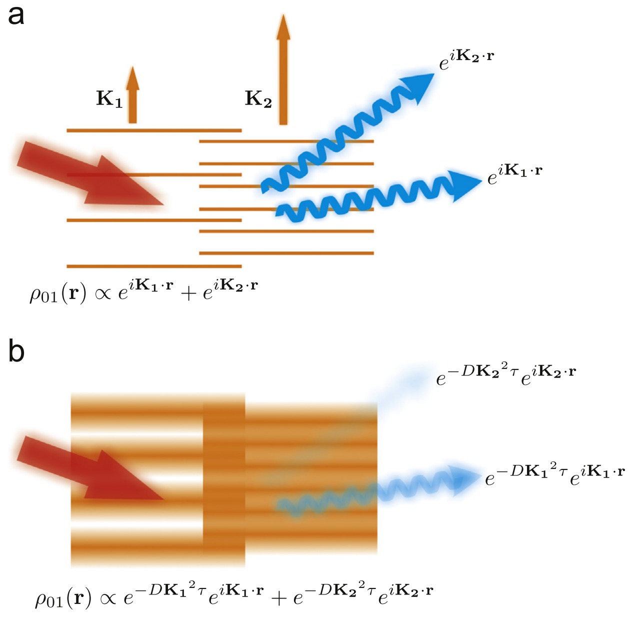

Fig. 1. (a) Planewave components of spatially dependent atomic coherence $\rho_{01}(\mathbf{r})$ act as diffraction gratings deflecting laser beam at different angles. (b) Components of high periodicity are blurred faster due to diffusion, therefore the intensity of deflected light will decay faster for higher angles of deflection. During storage time τ, the pattern component of specific periodicity corresponding to the wave vector $\mathbf{K}$ blurs with decay rate $D\mathbf{K}^2$, where D is the diffusion coefficient.

$$\frac{\partial}{\partial t}\rho_{01}(\mathbf{r},t) = D\nabla^2\rho_{01}(\mathbf{r},t) - \gamma_0\rho_{01}(\mathbf{r},t). \tag{1}$$

This equation can be readily solved in Fourier domain:

$$\rho_{01}(\mathbf{r},t) = e^{-\gamma_0 t}\sum_{\mathbf{K}}\beta(K)e^{-DK^2 t}e^{i\mathbf{K}\cdot\mathbf{r}}. \tag{2}$$

Evolution of each plane wave component of initial amplitude $\beta(K)$ and wave vector K is described by a simple exponential decay at a rate $\gamma(\mathbf{K}) = \gamma_0 + DK^2$. As long as the evolution of ρ_{01} can be described by Eq. (1) with position-independent homogeneous depolarization with a rate γ_0, the measurement of decay rates $\gamma(K)$ is sufficient to calculate D as a coefficient of the quadratic term of $\gamma(K)$.

2.2. Creation and probing of atomic coherence

In Fig. 2(a) we illustrated the atomic levels involved in Stokes scattering leading to creation of coherence $\rho_{01}(\mathbf{r})$ between levels $|0\rangle$ and $|1\rangle$. Upon spontaneous scattering of a laser beam detuned from the $|0\rangle \leftrightarrow |e\rangle$ transition both scattered light and atomic coherence are created. We shall consider a simple case where the laser beam and the scattered light are planewaves with wave vectors, $\mathbf{k_1}$ and $\mathbf{k_2}$, respectively. The difference between the laser field wave vector $\mathbf{k_1}$ and the created photons wave vector $\mathbf{k_2}$ is accumulated in atoms as a spatial phase of atomic coherence. As illustrated in Fig. 2(b) the atomic coherence created will be of a form $\rho_{01}(\mathbf{r}) = \beta e^{i\mathbf{K}\cdot\mathbf{r}}$, where $\mathbf{K} = \mathbf{k_1} - \mathbf{k_2}$.

Such periodic atomic coherence $\rho_{01}(\mathbf{r})$ can work as a diffraction grating and deflect a laser beam. This is realized in anti-Stokes scattering process presented in Fig. 2(c) in which laser beam detuned from the $|1\rangle \leftrightarrow |e\rangle$ transition is scattered at an angle. The spatial phase of atomic coherence $\rho_{01}(\mathbf{r})$ is imprinted back onto the scattered photons as follows from Bragg condition. Provided driving laser beam is the plane wave with a wave vector $\mathbf{k}_1'$, the diffracted light wave vector will be $\mathbf{k}_2' = \mathbf{k}_1' - \mathbf{K}$, as illustrated in Fig. 2(d). Therefore by observing the intensity of the light $I_{AS}(\theta)$ scattered at an angle θ, we register a signal which is proportional to the modulus square of the corresponding plane wave component of atomic coherence $|\beta(K)\exp(-\gamma(K)t)|^2$, with $\theta = K/k_1' = K\lambda/2\pi$.

2.3. Averaging and retrieving the diffusion coefficient

Spatially varying atomic coherence $\rho_{01}(\mathbf{r})$ is created in a spontaneous Stokes scattering process, which populates various planewave components randomly. Nonetheless, the average modulus square of the excitation amplitude $\langle|\beta(K)|^2\rangle$ created right after the scattering is set by the driving pulse parameters and can be kept constant between measurement series. Therefore, we can calculate the average intensity of the light scattered at a certain angle $\theta = K/k_1'$ and for a given storage time τ, incorporating Eq. (2):

$$\langle I_{AS}(\theta = K/k_1', \tau)\rangle = \eta(K)\langle|\beta(K)|^2\rangle e^{-2\gamma(K)\tau}, \tag{3}$$

where $\eta(K)$ is efficiency of readout, *a priori* dependent on K. The only factor that depends on the diffusion time τ is the intensity decay factor $e^{-2\gamma(K)\tau}$, which provides direct information about the decay rate $\gamma(K)$. Therefore for a given angle of