

# Suppression of Dephasing of Optically Trapped Atoms

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Ultra-cold atoms trapped in an optical dipole trap and prepared in a coherent superposition of their hyperfine ground states, decohere as they interact with their environment. We demonstrate that the loss in coherence in an "echo" experiment, which is caused by mechanisms such as Rayleigh scattering, can be suppressed by the use of a new pulse sequence. We also show that the coherence time is then limited by mixing to other vibrational levels in the trap and by the finite lifetime of the internal quantum states of the atoms.

PACS numbers:

Long coherence time of trapped atoms have attracted interest over the last years, not only because of their possible use in high precision spectroscopy, but mainly because many proposed quantum information processing schemes require manipulations of internal states of atoms/ions, and any dephasing or decoherence of these states will lead to loss of information. In the case of trapped atoms or ions many different approaches have been tried for increasing their coherence time. For trapped ions a "dephasing free subspace" was used to minimize the dephasing induced by the environment [1]. For neutral atoms and ions several "compensating" techniques have been demonstrated, in which the interaction causing the dephasing is canceled by an additional interaction of opposite sign [2]. Recently, three groups have reported the use of coherence echoes (an analogy to spin echoes [3]) for investigating the coherence of trapped alkali atoms and ions in a superposition state of two of their ground states [4][5][6]. In [5] the increased coherence time was used to study quantum dynamics of ultra cold atoms, and in [4] and [6] the study was related to quantum information processing with single ions and atoms.

In this letter we investigate the limitations on the coherence time achieved by echo techniques for ultra cold atoms trapped in an optical dipole trap. A new echo technique for improving the coherence time beyond the time achieved with the simple " $\pi/2$ - $\pi$ - $\pi/2$ " pulse sequence used in [4],[5] and [6] is demonstrated. The improved coherence time is achieved by the use of additional  $\pi$ -pulses between the two  $\pi/2$ -pulses. It relies on the fact that dephasing is not an instantaneous effect, and if the process is reversed before a complete dephasing has occurred, the latter can be suppressed. The method therefore has a strong parallel with the quantum Zeno effect [7], but we stress that it is not a utilization of this effect, since in our scheme no intermediate measurement is performed.

Any mechanism causing a change in the internal quantum state of an atom, will clearly cause a drop in the ensemble coherence. On the other hand, effects that lead

to dephasing but conserve the internal quantum state of the atom such as Rayleigh scattering of far detuned photons [8], slow fluctuations of the trap laser power and slow dynamics, will not cause an immediate decoherence but will lead to a dephasing that grows in time. The "multiple- $\pi$ " technique presented here can suppress dephasing from these mechanisms.

We study the coherence of the two magnetic insensitive ground states of  $^{85}\text{Rb}$  atoms trapped in a far-off-resonance optical dipole trap (FORT). These two levels ( $|5S_{1/2}, F=2, m_F=0\rangle$ , denoted  $|1\rangle$ , and  $|5S_{1/2}, F=3, m_F=0\rangle$ , denoted  $|2\rangle$ ) are separated by the hyperfine energy splitting  $E_{HF} = \hbar\omega_{HF}$  with  $\omega_{HF} = 2\pi \times 3.036$  GHz. Since the dipole potential is inversely proportional to the trap laser detuning  $\delta$  [9] there is a slightly different potential for atoms in different hyperfine states  $\delta V = V_2(\mathbf{x}) - V_1(\mathbf{x}) \simeq 2 \times 10^{-4} \times V_1$  for our experimental parameters. This means that the entire Hamiltonian can be written as:  $H = H_1|1\rangle\langle 1| + H_2|2\rangle\langle 2| = \left(\frac{p^2}{2m} + V_1(\mathbf{x})\right)|1\rangle\langle 1| + \left(\frac{p^2}{2m} + V_2(\mathbf{x}) + E_{HF}\right)|2\rangle\langle 2|$ , where  $p$  is the atomic center of mass momentum and  $V_1$  [ $V_2$ ] the external potential for an atom in state  $|1\rangle$  [ $|2\rangle$ ], much smaller than  $E_{HF}$ . The atoms are initially prepared in their internal ground state  $|1\rangle$ . Their total wave function can be written as  $\Psi = |1\rangle \otimes \psi$ , where  $\psi$  represents the vibrational (external degree of freedom) part of their wave function. A microwave (MW) field close to resonance with  $\omega_{HF}$  can drive transitions between the eigenstates of the Hamiltonian corresponding to different internal states. Since the radial size of our trap ( $\sim 50 \mu\text{m}$ ) is much smaller than the MW wavelength ( $\sim 10$  cm), the momentum of the MW photon can be neglected [9]. The transition matrix elements are thus given by  $C_{nn'} = \langle n' | n \rangle \times M_{1 \rightarrow 2}$  where  $M_{1 \rightarrow 2}$  is the free space matrix element for the internal state transition, and  $\langle n' | n \rangle$  is the overlap between the initial vibrational eigenstate of  $H_1$  and an eigenstate of  $H_2$  [10]. In [5] it was shown that for a large detuning of the FORT the potential difference  $\delta V$  is sufficiently small to ensure  $\langle n' | n \rangle \simeq \delta_{nn'}$ , for all populated  $|n\rangle$  of an

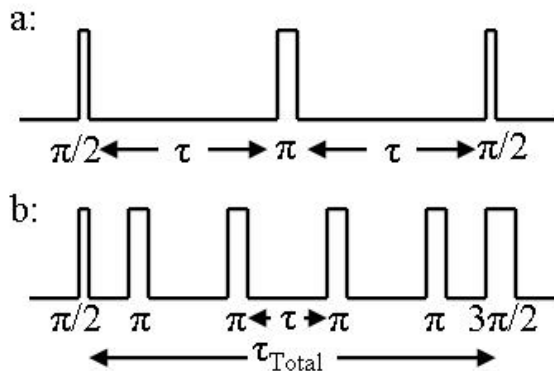


FIG. 1: a: Echo pulse sequence. b: multiple- $\pi$  pulse sequence.

atomic ensemble loaded into the FORT. Thus, the atomic ensemble acts as an inhomogeneously broadened ensemble of two-level systems, where the resonance frequency (energy splitting) of each one depends on the vibrational eigenstate of  $H_1$  initially occupied by the atom. This effect is a direct result of the quantization of the trap vibrational levels, and it is strikingly evident even for a thermal ensemble with  $k_B T \sim 10^6 \times$  mean level spacing (a condition that is often considered enough to ensure validity of classical mechanics) as in our experiment.

The echo pulse sequence consist of three pulses, two  $\pi/2$ -pulses with a  $\pi$ -pulse in between (see Fig. 1a). The first  $\pi/2$ -pulse creates a coherent superposition state of  $|1\rangle$  and  $|2\rangle$ . After a time  $\tau$  a  $\pi$ -pulse inverts the populations, and after another time  $\tau$  the atoms are exposed to a second  $\pi/2$ -pulse, after which the interference of the two parts of the wave function can be observed, as deviations of the populations of states  $|1\rangle$  and  $|2\rangle$  from  $1/2$ . For  $\langle n | n' \rangle \simeq \delta_{nn'}$ , the above model predicts that the echo pulse sequence will yield a perfect interference, i.e. all the population will return to  $|1\rangle$  [5]. As was demonstrated in [6] this is not always the case, in real systems.

Two types of mechanisms can cause the echo coherence to decay for long times. The first type of mechanisms (which can be denoted "dynamical"  $T_2$  processes) are processes leading to a time dependent resonance frequency of the two-level system. This will cause the two parts of the wave function generated by the first  $\pi/2$ -pulse to acquire different phases during the two "dark" periods of time  $\tau$ , hence causing imperfect interference at the time of the second  $\pi/2$ -pulse. Examples of such mechanisms are existence of fluctuations of the trap depth e.g. due to noise in the trap laser power [6], fluctuations in the bias magnetic field giving rise to a fluctuating second order Zeeman shift, collisions and spontaneous Rayleigh scattering of a photon from the trap laser. Rayleigh scattering of photons does not lead to instantaneous loss of coherence, as does a Raman scattering process [8]. Nevertheless, the recoil energy acquired by the atom can signif-

icantly change its trap vibrational level, and therefore its resonance frequency. The result is, again, a time dependent resonance frequency of the two level systems. Other heating mechanisms, such as pointing instability of the trap laser beam, typically involve a much smaller energy change than Rayleigh photon scattering, hence they induce a much longer time scale for dephasing.

The second type of mechanisms for decay of echo coherence ( $T_1$  processes) relates to the finite lifetime of the internal states of the atoms, which is limited mainly due to transitions induced by the trap laser light.

As stated above, dynamical  $T_2$  processes do not cause instantaneous decoherence, but require some time  $\tau_d$  for a substantial phase difference to evolve. For time between pulses  $\tau$  larger than  $\tau_d$ , we expect the coherent signal to disappear. The time  $\tau$  can be reduced by adding more (equally spaced in time)  $\pi$ -pulses, between the two  $\pi/2$ -pulses. We expect a coherent signal to reappear for  $\tau < \tau_d$ , when the decay of the echo coherence is dominated by dynamical  $T_2$  processes.

In our experiment  $^{85}Rb$  atoms are initially trapped in a magneto optical trap, then cooled to a temperature of  $20 \mu K$  and loaded into the FORT by an optical molasses stage, that also pumps the atoms into the  $F=2$  hyperfine state. The FORT consists of a 370 mW linearly polarized horizontal Gaussian laser beam focused to a  $1/e^2$  radius of  $50 \mu m$ , and with a wavelength of  $\lambda=810 nm$  yielding a trap depth of  $U_0 \approx 100 \mu K$ . The power of the FORT is stabilized by a feedback loop to a level of  $\sim 1\%$ . The transverse oscillation time of atoms in the trap is measured by parametric excitation spectroscopy to be 1.4 ms [11] ensuring  $\langle n' | n \rangle \simeq \delta_{n,n'}$ , for all thermally populated transverse vibrational states [5]. The free space Rabi-frequency of the atoms in the MW fields is 5 kHz. A bias magnetic field of 250 mG (turned on after the atoms are loaded into the trap) shifts all  $m_F \neq 0$  states out of resonance with the MW field, limiting the MW transitions to the two  $m_F = 0$  states ( $|1\rangle$  and  $|2\rangle$ ). After the MW pulses the population of state  $|2\rangle$  is detected by normalized selective fluorescence detection [5]. We subtract from the signal contributions to the population of  $|2\rangle$  due to F-changing Raman transitions induced by the trap laser and normalize to the signal after a short  $\pi$ -pulse.

As seen in Fig. 2, the echo signal starts from  $P_2 = 0$  (indicating perfect coherence) and monotonically approaches  $P_2 = \frac{1}{2}$  (indicating complete loss of coherence). The coherence time  $\tau_c$  is defined as the time  $\tau_{Total}$  between the two  $\pi/2$ -pulses where  $P_2$  reaches a value of  $P_2 = \frac{1}{2}(1 - \frac{1}{e})$ , and is seen to be  $\tau_c = 26$  ms (the decay time for the fringes in a Ramsey experiment is  $\sim 5$  ms). We verify that this coherence time is indeed not limited by longitudinal motion [10], by superimposing the trap with a  $\lambda=532 nm$  standing wave laser field that confines the atoms in the longitudinal direction of the trap and observing no improvement in the echo coherence time.

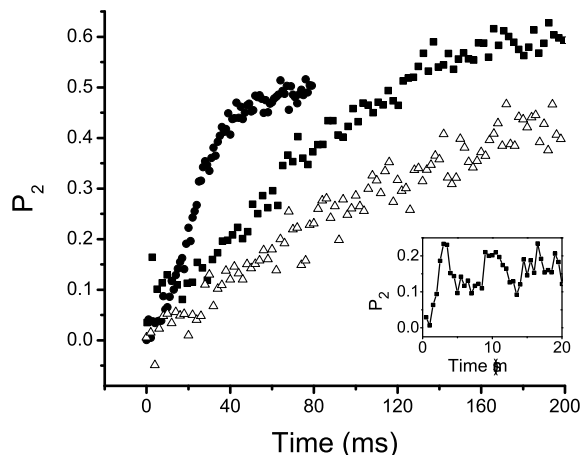


FIG. 2: ● : Coherence signal ( $P_2$ ) for the echo pulse sequence (Fig. 1a) as a function of  $\tau_{Total}$ . ■ :  $P_2$  for a pulse sequence with six  $\pi$ -pulses (Fig. 1b) as a function of  $\tau_{Total}$ . It is seen that adding more  $\pi$ -pulses increases the coherence time, but also leads to an initial small and rapid partial coherence decay. In the inset the short time signal for a pulse sequence with ten  $\pi$ -pulses is shown. Wave-packet revivals are seen for  $\tau_{Total}=7$  and 14 ms.  $\Delta$  :  $P_2$  for a  $\pi$ - $\pi$  pulse sequence as a function of  $\tau_{Total}$ . A monotonic increase in the signal is seen, due to transitions between  $m_F$ -states within the same F-manifold.

Next, we add more  $\pi$ -pulses using the pulse sequence shown in Fig. 1b. First a  $\pi/2$ -pulse creates a coherent superposition state of  $|1\rangle$  and  $|2\rangle$ . After time  $\tau/2$  the first  $\pi$ -pulse is applied, followed by the rest of the  $\pi$ -pulses at time intervals  $\tau$ . We end the sequence with a  $3\pi/2$ -pulse at time  $\tau/2$  after the last  $\pi$ -pulse in order to have  $P_2 = 0$  for a coherent signal for the even number of  $\pi$ -pulses that we use. The signal as a function of the total time between the first and the last pulse,  $\tau_{Total}$ , for a pulse sequence containing six  $\pi$ -pulses is also shown in Fig. 2. It is seen that  $\tau_c = 65$  ms, clearly showing that the additional  $\pi$ -pulses substantially increase the coherence time.

As shown in Fig. 2, adding more  $\pi$ -pulses leads to an initial small and rapid partial loss of coherence. This is because  $\langle n' | n \rangle$  is not strictly a delta function, hence when more  $\pi$ -pulses are added, the mixing to other transverse levels is increased and the dynamical effects discussed in [5] appear (The asymptotic value of  $P_2$  due to this mixing effect is  $\frac{1}{2}(1 - \langle n' | n \rangle^{2(n_\pi+1)})$  where  $n_\pi$  is the number of  $\pi$ -pulses. The effect is too weak to be observed for  $n_\pi = 1$ ). Shown in the inset, is the short time coherence signal for a sequence with 10  $\pi$ -pulses. Wave packet revivals appear for time  $\tau_{Total} = 7$  and 14 ms (time between  $\pi$ -pulses of 0.7 and 1.4 ms) as expected for a harmonic trap with our measured transverse oscillation time of 1.4 ms [5].

In Fig. 3 the coherence time is shown as a function of the number of  $\pi$ -pulses. It is seen that the coherence time initially shows linear dependence on the number of  $\pi$ -

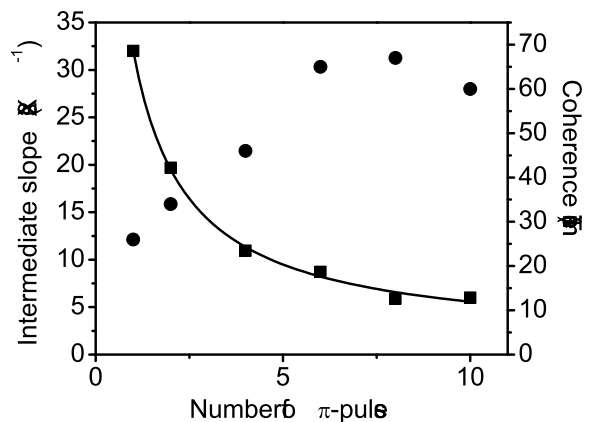


FIG. 3: ● : Coherence time as a function of the number of  $\pi$ -pulses. A maximum coherence time of  $\sim 65$  ms is observed, as a consequence of a trade-off between suppressing  $T_2$ -processes and the increased mixing to different transverse vibrational states [5]. ■ : Twice the slope of the intermediate regime, corrected for contributions from F-conserving transitions. Solid line: Fit to ■. The infinite many  $\pi$  decoherence rate is extrapolated from the fit, to yield a rate of  $1.3 s^{-1}$

pulses and then flattens out with a maximum value of  $\sim 65$  ms, a 2.5 fold improvement as compared to the simple echo coherence time. The maximum coherence time is given by a trade-off between suppressing the dephasing due to  $T_2$  processes by adding more  $\pi$ -pulses and the increased dephasing due to the mixing to other transverse states, that the additional  $\pi$ -pulses induce.

The  $P_2$  signal for a sequence with six  $\pi$ -pulses exceeds 1/2 at long times. We attribute this to a weak population mixing between our "two-level" system, composed of levels  $|1\rangle$  ( $|F=2, m_F=0\rangle$ ) and  $|2\rangle$  ( $|F=3, m_F=0\rangle$ ) and the  $m_F \neq 0$  Zeeman states in the ground state hyperfine manifold [12]. While our F-selective detection normalizes and accounts for the F-changing transitions, it cannot account for F-conserving,  $m_F$ -changing, transitions.

To isolate and directly measure the amount of coupling to other  $m_F$ -states we measure the population of  $F=3$  as a function of time between two population-inverting  $\pi$ -pulses, where no interference is involved. The results, also presented in Fig. 2, clearly show that the population of  $F=3$  increases as a function of time between such two  $\pi$ -pulses, a fact that can only result from coupling to the other  $m_F$ -states [13]. From the initial slope of this  $\pi$ - $\pi$  measurement the F-conserving transition rate is estimated as  $1.2 s^{-1}$  [14]. The F-changing transition rate was measured independently to be  $0.6 s^{-1}$ . Combining these two rates yields a rate of  $1.8 s^{-1}$ .

To investigate the ability of the multiple- $\pi$  scheme to suppress dephasing due to dynamical  $T_2$  processes, we are interested in the slope of the intermediate decay (see Fig. 3), found by fitting the intermediate section of the data sets with a straight line, corrected for the long time

slope, thereby neglecting the effect of transverse motion and F-conserving transitions (we show twice the slope since the decay of coherence contribute only  $1/2$  to  $P_2$ ). We see that the addition of  $\pi$ -pulses improves the intermediate slope by a factor of 6. To find the limiting value for the slope we assume that dephasing from dynamical  $T_2$  processes is suppressed linearly with the number of  $\pi$ -pulses  $n_\pi$ . The data set is then fitted with the function  $a + b/(n_\pi - c)$ , and the limiting value  $a$  is found to be  $a=1.3\pm 0.8 \text{ s}^{-1}$  indicating that the above estimated total decay rate from the  $m_F=0$  states of  $1.8 \text{ s}^{-1}$  plays a dominating role.

It should be noted that the geometrical shape of the trap determines weather processes such as trap power fluctuations and Rayleigh Scattering lead to dynamical  $T_2$ -processes. This can be exploited to design a "dephasing free" trap, as proposed in [15] in order to overcome the dephasing due to inhomogeneous stark shift. In this trap also many of the above listed processes will not lead to time dependent resonance frequency of the two level systems.

In summary we demonstrated that the dephasing in MW spectroscopy of optical trapped atoms due to dynamical  $T_2$  processes can be suppressed beyond the suppression offered by the simple echo, by using an improved pulse sequence containing additional  $\pi$ -pulses. The achieved coherence time is limited by increased mixing between transverse states, and to a lesser extent the lifetime of the internal states of the atoms. Both these factors are expected to be substantially smaller for trap laser with much larger detuning, such as in [6]. This improvement is of potential importance to the field of quantum information where long coherence times are of great importance [4][6]. Finally, the demonstrated pulse sequence may also find use in precision spectroscopy of a periodic effect, where the  $\pi$ -pulses can be synchronized with the period of that effect.

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- [1] D. Kielpinski, V. Meyer, M. A. Rowe, C. A. Sackett, W. M. Itano, C. Monroe, and D. J. Wineland, *Science*, **291** 1013 (2001).  
 [2] T. Ido, Y. Isoya and, H. Katori, *Phys Rev. A* **61**, 061403 (2000); H. J. Lewandowski, D. M. Harber, D. L. Whitaker, and E. A. Cornell, *Phys. Rev. Lett.* **88**, 070403

- (2002); A. Kaplan, M. F. Andersen, and N. Davidson, *Phys Rev. A* **66**, 045401 (2002); H. Haffner, S. Gulde, M. Riebe, G. Lancaster, C. Becher, J. Eschner, F. Schmidt-Kaler, and R. Blatt, *Phys. Rev. Lett.* **90**, 143602 (2003).  
 [3] E. L. Hahn, *Phys. Rev.* **80**, 580 (1950).  
 [4] M. A. Rowe et. al., *Quantum Information and Computation.* **2** 257 (2002).  
 [5] M. F. Andersen, A. Kaplan, and N. Davidson, *Phys. Rev. Lett.* **90**, 023001 (2003).  
 [6] S. Kuhr, W. Alt, D. Schrader, I. Dotsenko, Y. Miroshnychenko, W. Rosenfeld, M. Khudaverdyan, V. Gomer, A. Rauschenbeutel, and D. Meschede, arXiv:quant-ph/0304081.  
 [7] B. Misra and E. C. G. Sudarshan, *J. Math. Phys.* **18**, 756 (1977); W. M. Itano, D. J. Heinzen, J. J. Bollinger, and D. J. Wineland, *Phys. Rev. A* **41**, 2295 (1990); M. C. Fischer, B. Gutiérrez-Medina, and M. G. Raizen, *Phys. Rev. Lett.* **87**, 040402 (2001).  
 [8] R. A. Cline, J. D. Miller, M. R. Matthews, and D. J. Heinzen, *Optics Lett.* **19**, 207 (1994).  
 [9] C. Cohen-Tannoudji, J. Dupont-Roc and G. Grynberg, *Atom-Photon interactions*, John Wiley & Sons Inc. (1992).  
 [10] The longitudinal oscillation time in the FORT is  $\sim 450$  ms, which is sufficiently long so longitudinal motion will not play a role in our experiment, since it is suppressed by the multiple- $\pi$  technique. Therefore in the following  $|n\rangle$  refers to eigenstates of the transverse motion.  
 [11] S. Friebe, C. D'Andrea, J. Walz, M. Weitz, and T. W. Hansch, *Phys. Rev. A* **57**, R20 (1998).  
 [12] After the first  $\pi/2$  pulse level  $|1\rangle$  is less populated than each of the  $|F = 2, m_F \neq 0\rangle$  states and level  $|2\rangle$  is more populated than each of the  $|F = 3, m_F \neq 0\rangle$  states. Hence, the net effect of F-conserving transitions is to increase the population of the  $F=3$  manifold after the subsequent MW pulses.  
 [13] To further support our interpretation we verified that the asymptotic slope of the multiple- $\pi$  measurement was indeed half the slope of the  $\pi$ - $\pi$  measurement, as expected from the fact that the  $m_F$  population difference of the former is roughly half that of the latter.  
 [14] The F-conserving  $m_F$ -changing transition rate is not set entirely by spontaneous Raman transitions. Due to slight polarization imperfections, there is also a contribution from off-resonant stimulated Raman transitions involving two photons from the trap laser. This was verified by repeating the  $\pi$ - $\pi$  measurements for different strength of the bias magnetic field, and observing a reduction in the transition rate for larger bias.  
 [15] M. F. Andersen, A. Kaplan, T. Grünzweig, and N. Davidson. *Communications in Nonlinear Science and Numerical Simulations*, **8**, 289 (2003).