Echo Spectroscopy and Quantum Stability of Trapped Atoms

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We investigate the dephasing of ultra cold ^{85}Rb atoms trapped in an optical dipole trap and prepared in a coherent superposition of their two hyperfine ground states by interaction with a microwave pulse. We demonstrate that the dephasing, measured as the Ramsey fringe contrast, can be reversed by stimulating a coherence echo with a π pulse between the two $\frac{\pi}{2}$ pulses, in analogy to the photon echo. We also demonstrate that "echo spectroscopy" can be used to study the quantum dynamics in the trap even when more than 10^6 states are thermally populated and to study the crossover from quantum to classical dynamics.

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The process of decoherence/dephasing is crucial to our understanding of the connection between quantum mechanics and classical physics, since it is the mechanism by which a pure quantum state evolves into a mixture of states when the system is coupled to the environment. In the field of quantum information long coherence times are of outmost importance, since decoherence or dephasing represent loss of information, or decrease in "fidelity." Long coherence times of atomic ensembles prepared in superposition states are of importance to high precision spectroscopy, where the measurement time is a limiting factor on the precision of the measurement. It is important to distinguish between reversible processes (dephasing) and irreversible processes (decoherence). Dephasing can be reversed, at least partially, by stimulating an effective "time reversal," as has been reported for spin echoes [1] and photon echoes [2] and more recently for a motional wave packet echo using ultra cold atoms in a one-dimensional optical lattice [3].

Microwave (MW) spectroscopy has been previously performed on ultra cold trapped atoms where long measurement times hold promise for high spectral resolution [4]. However, dephasing due to inhomogeneous trap pertubations limits the applicability of trapped atoms for precision spectroscopy. Recently, a MW Ramsey technique was used to investigate the coherence of accelerator modes in an atom-optical realization of the δ-kicked accelerator [5].

In this letter we investigate the dephasing of ultra cold ^{85}Rb atoms trapped in an optical dipole trap and prepared in a coherent superposition of the two hyperfine ground states by interaction with a so-called $\frac{\pi}{2}$ MW pulse. We demonstrate that the dephasing, measured as the Ramsey fringe contrast decay [6] and related with the Loschmidt echo decay [7], can be reversed (for the proper trap parameters), by stimulating a *coherence echo*. The latter is obtained by adding a population-inverting "π" pulse between the usual two "$\frac{\pi}{2}$" pulses. We also show that the failure of the echo for other trap parameters is due to dynamics in the trap, and thereby that echo spectroscopy can be used to gain important information about the time correlation function of the dynamics.

We study the two hyperfine levels of the ground state of ^{85}Rb atoms trapped in a dipole trap. 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 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 δ [8] there is a slightly different potential for atoms in different hyperfine states [9]. This difference in potential is the origin of the dephasing mechanisms we study here.

For spectroscopy of trapped atoms we must consider the entire Hamiltonian including both the internal and the (center of mass) motional degrees of freedom of the atom. The external potential differs for the two levels, and the Hamiltonian of our trapped two-level atom can be written as $H = H_1|1\rangle\langle 1| + H_2|2\rangle\langle 2| = (\frac{p^2}{2m} + V_1(\mathbf{x})) \times |1\rangle\langle 1| + (\frac{p^2}{2m} + V_2(\mathbf{x}) + E_{HF})|2\rangle\langle 2|$, 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 ψ represents the motional (external degree of freedom) part of their wave function. If a MW field close to resonance with ω_{HF} is applied, transitions between the eigenstates of the Hamiltonian corresponding to different internal states can be driven. Since the size of our trap ($\sim 50\ \mu$m) is much smaller than the MW wavelength (~ 10 cm), the momentum of the MW photon can be neglected (Lamb-Dicke regime [8]). The transition matrix elements are given by $C_{nn'} = \langle n' \mid n\rangle \times M_{1\to 2}$, where $M_{1\to 2}$ is the free space matrix element for the internal state transition, and $\langle n' \mid n\rangle$ is the overlap between the initial motional eigenstate of H_1 and an eigenstate of H_2. When a strong and short MW pulse is applied, the motional part of the initial wave function is simply projected into $V_2(\mathbf{x})$. If $V_1(\mathbf{x}) = V_2(\mathbf{x})$ then clearly

$\langle n' \mid n \rangle = \delta_{nn'}$. For a small enough "perturbation," we will still have $\langle n' \mid n \rangle \simeq \delta_{nn'}$. In the general case, a projected eigenstate of H_1 will not be an eigenstate of H_2, and therefore will evolve in the new potential, causing the overlap $|\langle n(t=0) \mid n(t=\tau)\rangle|$ to decay ($|n(t=\tau)\rangle \equiv \exp(-i\frac{H_2}{\hbar}\tau)|n\rangle$).

In Ramsey spectroscopy, two $\pi/2$ pulses are applied, separated by a variable time τ. If we start with some eigenstate of H_1 characterized by the quantum number n, then the probability to be in the internal state $|2\rangle$ after the $\pi/2$-$\pi/2$ pulse sequence can be shown to be $P_2 = \frac{1}{2}[1 + \langle n|e^{-i[(H_2/\hbar)-\omega_{\mathrm{MW}}+\Delta_n]\tau}|n\rangle\cos(\Delta_n\tau)]$, where ω_{MW} is the MW frequency, τ is the time between the pulses, and Δ_n is a generalized, state dependent, detuning (it reduces to the detuning when only two levels are coupled by the MW field) defined so $\langle n|\exp[-i(\frac{H_2}{\hbar} - \omega_{\mathrm{MW}} + \Delta_n)\tau]|n\rangle$ is real and positive. Scanning ω_{MW} for a fixed τ yields the usual Ramsey fringes with a contrast given by $\langle n|\exp[-i(\frac{H_2}{\hbar} - \omega_{\mathrm{MW}} + \Delta_n)\tau]|n\rangle = |\langle n(t=0) \mid n(t=\tau)\rangle|$. The fringe contrast can be viewed as the survival probability for a state $|n\rangle$ after a sudden change in potential from $V_1(\mathbf{x})$ to $V_2(\mathbf{x})$. Also, since $\langle n|\exp[-i(\frac{H_2}{\hbar} - \omega_{\mathrm{MW}} + \Delta_n)\tau]|n\rangle = |\langle n|\exp[i(\frac{H_1}{\hbar})\tau]\exp[-i(\frac{H_2}{\hbar})\tau]|n\rangle|$ it serves as a measure of the stability of the quantum evolution under a small perturbation in the Hamiltonian [10].

In our experiment we do not have an initial single motional eigenstate, but a thermal ensemble of atoms incoherently populating more than 10^6 eigenstates. The total population in $|2\rangle$ will be given by an average of P_2 over the initial thermal ensemble. Δ_n depends on the initial state, and due to this spread in detuning the fringe contrast of the ensemble-averaged P_2 decays rapidly even when $|\langle n(t=0) \mid n(t=\tau)\rangle| \simeq 1$ for all populated states.

Our experiment is as follows: ^{85}Rb atoms are laser cooled to a temperature of 20 μK, optically pumped into the $F = 2$ hyperfine state, and loaded into a far off resonance optical trap (FORT). The FORT consists of a 50 mW horizontal laser beam focused to a $1/e^2$ radius of 50 μm, and with a wavelength of $\lambda = 800$ nm (~ 5 nm from the D_1 line) yielding a trap depth of $U_0/k_bT = 1.5$. The longitudinal oscillation time in the FORT (~ 500 ms) is much larger than the experiment time (of the order of 10 ms), and hence only the transverse motion is considered. The transverse oscillation time was measured using parametric excitation spectroscopy [11] to be 3.6 ms, in good agreement with the calculated value of 3 ms. For these trap parameters $\langle n' \mid n \rangle \simeq \delta_{n',n}$, and therefore $|\langle n(t=0) \mid n(t=\tau)\rangle| \simeq 1$ for all thermally populated states. The free space Rabi frequency of the MW fields is 5 kHz, so the duration of the MW pulses can be neglected. A bias magnetic field of 40 mG 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 [12], and the Ramsey fringe contrast is normalized to the number of atoms in $|2\rangle$ with a short π pulse.

As seen in Fig. 1, the Ramsey fringe contrast decays on a time scale of a few ms, due to the variation of Δ_n over the thermally populated states in good agreement with a calculated decay time of 2.7 ms. The decay time is calculated as $1/(2\Delta_{\mathrm{RMS}})$, where Δ_{RMS} is the rms spread of the resonance frequencies for $|n\rangle \rightarrow |n' = n\rangle$ transitions, taken over a thermal ensemble in a harmonic trap clipped at $1.5k_BT$. As explained above, the observed decay of the Ramsey fringe contrast is not a fingerprint of decoherence, but a consequence of dephasing. This dephasing can be reversed by adding a MW π pulse between the two $\frac{\pi}{2}$ pulses, which inverts the populations of $|1\rangle$ and $|2\rangle$. P_2 then becomes

$$\begin{aligned} P_2 &= \tfrac{1}{2}[1 - \mathrm{Re}(\langle n|e^{i(H_1/\hbar)\tau}e^{i(H_2/\hbar)\tau}e^{-i(H_1/\hbar)\tau}e^{-i(H_2/\hbar)\tau}|n\rangle)] \\ &= \tfrac{1}{2}[1 - \mathrm{Re}(e^{i(E_n^1/\hbar)\tau}\langle\varphi_n(t=0) \mid \varphi_n(t=\tau)\rangle)], \end{aligned} \quad (1)$$

where $\{\varphi_n\}$ is a new basis defined by $|\varphi_n(t=0)\rangle \equiv \exp[-i(H_2/\hbar)\tau]|n\rangle$, and $|\varphi_n(t=\tau)\rangle \equiv \exp[-i(H_1/\hbar)\tau] \times |\varphi_n(t=0)\rangle$ [13]. P_2 no longer depends on ω_{MW} and E_{HF}. The condition $\langle n'|n\rangle \simeq \delta_{nn'}$ for all initially populated vibrational states now ensures that $P_2 \simeq 0$ for all τ. In other words, after dephasing for a time τ a π pulse stimulates a *coherence echo at* time 2τ. The results of $\pi/2$-π-$\pi/2$ echo spectroscopy with the same trap parameters as before are also presented in Fig. 1. A coherence echo ($P_2 \ll 1/2$) is clearly seen long after the Ramsey fringe contrast has decayed. On a time scale of $\sim$100 ms the echo coherence decays, presumably due to longitudinal motion and photon scattering from the trap laser.

When $\langle n' \mid n \rangle \neq \delta_{nn'}$ a good echo signal is no longer expected, since each vibrational state is coupled to several vibrational states by the MW fields, and therefore

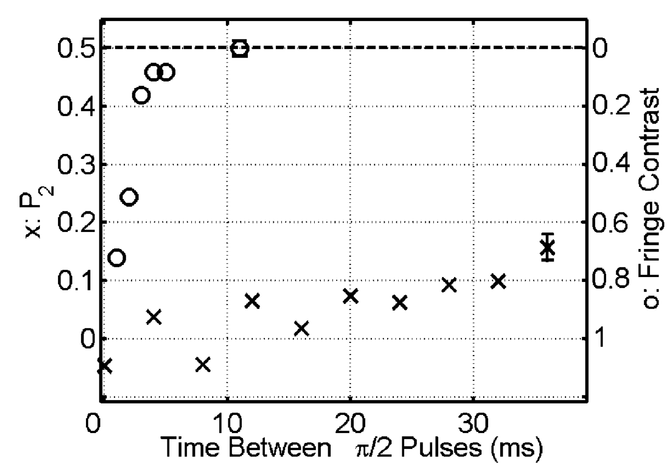

FIG. 1. Ramsey fringe contrast (○) and echo signal (×) measured as a function of time between $\pi/2$ pulses. For the echo signal the value 0 represents complete coherence, and the value 1/2 represents complete dephasing. Trap laser wavelength is 800 nm. A coherent echo ($P_2 \ll 1/2$) persists long after the fringe contrast has decayed. The statistical uncertainty of each data set is indicated by error bars on the last point.

$|\langle\varphi_n(t=0) \mid \varphi_n(t=\tau)\rangle| < 1$. We perform echo spectroscopy as a function of time between pulses for different wavelengths of the trap laser, thereby changing the perturbation strength δV [9], while keeping the trap depth constant by adjusting the power of the trap beam. The results are shown in Fig. 2. For a large detuning ($\lambda = 805$ nm, 10 nm from the D_1) a good echo ($P_2 \ll 1/2$) is seen independent of the time between pulses, as also seen in Fig. 1. For an intermediate detuning ($\lambda = 798.25$ nm) damped oscillations to a level smaller than 1/2 are seen, and for a small detuning ($\lambda = 796.25$ nm) a complete decay of the echo coherence ($P_2 = 1/2$) followed by partial revivals at later times is seen.

The interpretation of the large detuning regime was given above. For intermediate detunings a small but significant coupling to other ($n' \neq n$) vibrational states exists. Ignoring gravity, $V_1(\mathbf{x})$ and $V_2(\mathbf{x})$ are just the optical potentials and are related by $V_2(\mathbf{x}) = (1+\varepsilon)V_1(\mathbf{x})$ [9]. When atoms are transferred from $V_1(\mathbf{x})$ to $V_2(\mathbf{x})$ by the MW field, a parametric excitation of the atomic wave packet is induced, thereby exciting breathing modes. However, the change in the optical potential also changes the gravitational sag, and hence excites sloshing modes along the vertical axis. A wave function parametrically excited in an harmonic oscillator will revive after $\tau = m \times 1/2\tau_{\rm osc}$ (yielding $|\langle\varphi_n(t=0) \mid \varphi_n(t = m \times 1/2\tau_{\rm osc})\rangle| = 1$), and a sloshing mode will revive after $\tau = m \times \tau_{\rm osc}$ [3,14,15]. These revivals are seen in the middle curve of Fig. 2 as a partial revival in the echo signal at $\tau = 1.8$ ms and a better one at $\tau = 3.6$ ms. For the upper curve in Fig. 2, a clear revival is seen at $\tau \sim 3.3$. The origin of these revivals was verified in numerical calculations of the echo signal for typical single states in a 2D harmonic oscillator. A similar calculation showed that, without the effect of gravity, the revival at $\tau = 1.8$ ms was complete. The damping of the oscillation of the echo signal, i.e., the lack of a perfect revival at $\tau = \tau_{\rm osc}$, is attributed to the anharmonicity of the Gaussian trap. We stress the sensitivity of our technique to map the quantum dynamics of a system, since we see the dynamics due to a pertubation (kick), that is about 3 orders of magnitude smaller than $k_B T$.

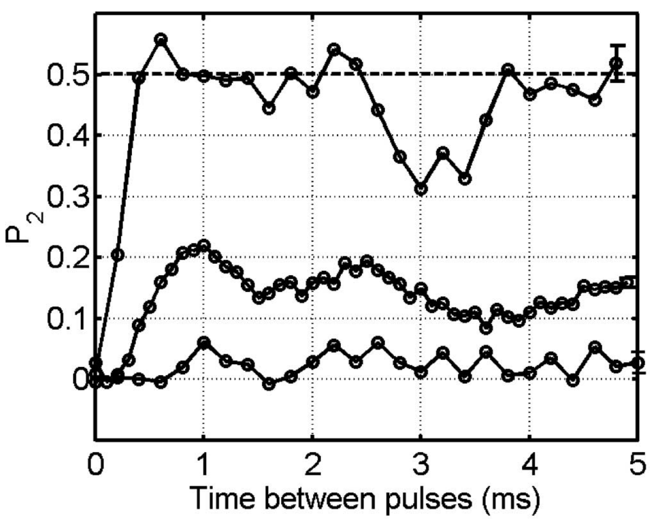

FIG. 2. Echo signal P_2 measured for three different trap laser wavelengths λ. Lower curve: $\lambda = 805$ nm. A good echo signal ($P_2 \ll 1/2$) is seen almost independent of time between pulses. Middle curve: $\lambda = 798.25$ nm. The echo signal oscillates around a value smaller than 1/2 with partial revivals at $\tau = 1/2\tau_{\rm osc}$ and $\tau = \tau_{\rm osc}$, where $\tau_{\rm osc} = 3.6$ ms is the measured trap oscillation frequency in the transverse direction. Upper curve: $\lambda = 796.25$ nm. After a short time the echo signal completely disappears ($P_2 = 1/2$), but partly revives again at $\tau = 3.3$ ms, close to $\tau_{\rm osc}$. Error bars on the last point indicate the statistical uncertainty.

For sufficiently long-time τ the wave packet oscillations of Fig. 2 damp due to complete dephasing of the dynamics. At such long time a simple expression for the echo signal can be given. In particular, assuming random phases between all vibrational states yields the simple relation $|\langle\varphi_n(t=0) \mid \varphi_n(t=\tau)\rangle| = |\langle n' = n \mid n\rangle|^4$. Substituting this into Eq. (1) and averaging over the ensemble yields the expected long-time echo signal. We performed this calculation numerically for a 2D harmonic trap, in gravity, with our measured oscillation frequency and a thermal ensemble with a temperature of 20 μK clipped at our trap depth of $1.5k_BT$ [16]. The results are shown in Fig. 3, together with the measured long-time echo signals as a function of potential difference. As seen, the calculation for the harmonic trap and the data points for the Gaussian trap show the same qualitative behavior of improved long-time echo when δV becomes small.

Finally, nonvanishing matrix elements for transitions to vibrational states with $n' \neq n$ should show up as sidebands in the MW spectrum, if the pulse is long and weak enough so that the power broadening is smaller than the typical level spacing. This is shown in Fig. 4 for a trap

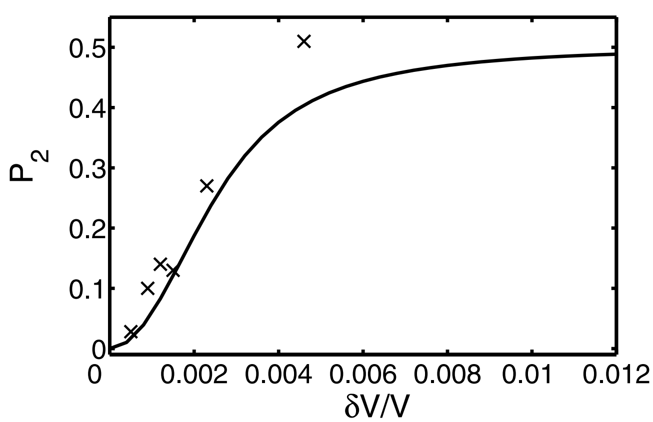

FIG. 3. $\times$: long time level of measured echo signal as a function of difference between potentials ($\delta V/V$). Solid line: calculation of the ensemble average of $|\langle n' = n \mid n\rangle|^4$ (a measure of the quantum stability of the system) for a 2D harmonic potential with oscillation time of 3.6 ms [16].

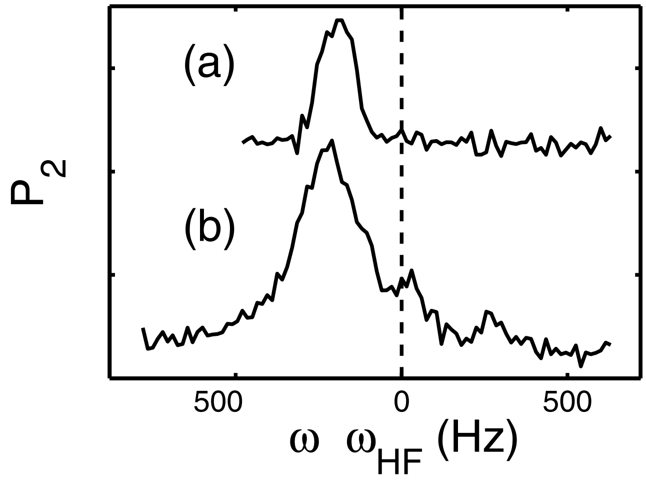

FIG. 4. MW spectroscopy of atoms in a trap at a wavelength of 805 nm, with a 20 ms MW pulse. MW-power equivalent of (a) a free-space π pulse and (b) a free-space 4π pulse.

laser wavelength of 805 nm. For a MW pulse area corresponding to a free space π pulse [Fig. 4(a)], the sidebands are not visible, indicating that the matrix elements for the sidebands are very small and thus enabling a successful echo in agreement with Fig. 2. Only for the much stronger 4π pulse [Fig. 4(b)], the sidebands emerge. We also verified that the sidebands are stronger for smaller detunings, as expected from the analysis. This is interesting because it allows the quantization of the trap levels to be detected, even at very large temperatures compared to the 1D level spacing ($k_B T > 10^3 \times \hbar\omega_{\mathrm{osc}}$), where the motion of particles is usually considered to be classical.

In summary, we have demonstrated that a macroscopic coherence, lost as a consequence of dephasing of the different populated motional levels, can be efficiently revived by stimulating an echo if the trap detunings is large enough so $|\langle n' = n \mid n \rangle| \simeq 1$. This suppression of dephasing due to pertubations induced by the trap yields a dramatic increase in the coherence time for trapped atoms that may find important applications for precision spectroscopy and quantum information processing. We also demonstrated that echo spectroscopy can be used to experimentally map the quantum dynamics of trapped atoms, namely, the ensemble average of $|\langle \varphi_n(t = 0) \mid \varphi_n(t = \tau) \rangle|$, showing a crossover between quantum and classical regimes. In this way it can serve as an extremely sensitive experimental tool for investigating quantum chaos in atom-optics billiards [17] even when more than 10^6 states are thermally populated. Finally, we demonstrated that for sufficiently large detunings the sidebands can be resolved, thus making it possible to select monoenergetic atoms by help of MW pulses, and thereby enabling energy-dependent repumping with MW pulses, for new cooling schemes.

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