Non-Destructive Probing of Rabi Oscillations on the Cesium Clock Transition near the Standard Quantum Limit

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(Dated: February 3, 2008)

We report on non-destructive observation of Rabi oscillations on the Cs clock transition. The internal atomic state evolution of a dipole-trapped ensemble of cold atoms is inferred from the phase shift of a probe laser beam as measured using a Mach-Zehnder interferometer. We describe a single color as well as a two-color probing scheme. Using the latter, measurements of the collective pseudo-spin projection of atoms in a superposition of the clock states are performed and the observed spin fluctuations are shown to be close to the standard quantum limit.

PACS numbers: 42.50.Lc, 42.50.Nn, 06.30.Ft, 03.65.Ta

The problem of a two-level atom interacting resonantly with a coherent radiation field is of general importance to the field of atomic and optical physics, and quantum optics [1]. Two-level quantum systems and the ability to manipulate them coherently are essential to today’s atomic clocks [2] and tomorrow’s quantum computers [3]. The coherence life times in these systems can be measured via the decay of population oscillations when subjected to an external resonant drive field. Such Rabi oscillations are routinely observed in quantum dots [4], Josephson junction qubits [5], nitrogen-vacancy centers in diamond [6], as well as for trapped ions [7] and atoms [8]. In the case of trapped ions and atoms the internal quantum state $| \uparrow \rangle$ or $| \downarrow \rangle$ is typically detected via spontaneously scattered photons when probing the atoms with laser light resonant with a transition from one of the states to an auxiliary level. This method instantaneously destroys the coherence between states $| \uparrow \rangle$ and $| \downarrow \rangle$ interrupting the Rabi oscillations at the time of probing. To sample the Rabi oscillations at given instances of time requires at least as many re-preparations of the quantum system [9]. Rather than performing a completely destructive measurement on an atomic sample, it is possible to gain information about the quantum state in a more gentle fashion by using off-resonant probe light and considering the ensemble of atoms as a refractive medium. Such non-destructive probing could, e.g., prove advantageous to optical lattice clocks [10] or to the manipulation of cold atoms. We employ a pulsed probing scheme to take advantage of cold atomic ensemble is measured using a Mach-Zehnder (MZ) interferometer (shown schematically in Fig. 1), which compares the phase accumulated by a laser beam in a probe arm to that of a spatially separated reference arm. The atoms are located in the probe arm and modifies the optical path length according to their internal quantum state. As compared to the polarization scheme [12] the MZ interferometer provides a refractive index change per atom which is larger since the reference beam is not phase shifted by the atoms. We employ a pulsed probing scheme to take advantage of ac photo detectors characterized by very low electronic noise compared to typical dc detectors. This allows to reduce the number of probe photons and thus to minimize the destructive nature of the atomic measurement. In particular, our detection of light is shot noise limited, which in turn allows for for the best detection of atomic spin noise. Finally, rather...
than being released from a magneto-optical trap (MOT), our atomic sample is confined by an optical dipole trap resulting in a denser sample, available for an extended period of time. As shown in [14], the optical depth of the atomic ensemble is the key parameter for optimum gain of information about the collective quantum state versus its destruction.

Our experimental setup has been described in detail in [15]. In brief, Cs atoms are loaded from a MOT into an optical dipole trap, where the atomic sample has a diameter of ~60 μm and contains up to $5 \times 10^5$ atoms, achieving an optical depth around 25 as suggested by [14]. The trapped sample is located in one arm of our MZ interferometer as shown in Fig. 1. The geometric path length difference between the two arms of the interferometer is locked by a piezo-actuated mirror using a weak auxiliary far-off-resonance laser beam counter-propagating the atomic probe beam. To minimize the influence of the laser phase noise of the locking and the probe beams, the interferometer is aligned to the so-called white light position, where the two arms have equal length. After loading the dipole trap we apply a small vertical bias field $\sim 1$ G to define a quantization axis and optically pump the atoms to the $(F = 4, m_F = 0) \equiv |1\rangle$ clock state using vertically polarized laser light driving $6S_{1/2}(F = 4, m_F \neq 0) \rightarrow 6P_{3/2}(F' = 4) \pi$-transitions. An additional repumping laser beam resonant with the $6S_{1/2}(F = 3) \rightarrow 6P_{3/2}(F' = 4) \pi$-transitions ensures that the atoms do not accumulate in the $F = 3$ ground level. We end up with up to 80% of the atoms in $|1\rangle$ with an efficiency likely to be limited by $m_F$-coherences created by our narrow-bandwidth ($\sim 250$ kHz) pumping lasers [16].

We address the clock states with 9.2 GHz microwave radiation generated by a precision synthesizer. The orientation of the linearly polarized magnetic field vector of the microwave field is parallel to the guiding bias field of the atoms so that it only drives magnetic dipole $\pi$-transitions. We have full control over the power, frequency, relative phase, and duration of the microwave field, so that we can produce any target state on the generalized Bloch sphere of the effective two level system [1]. As discussed in [15,17] the phase shift of a light beam with polarization state $q$ and wavelength $\lambda$ propagating a distance $l$ through an atomic gas with population $N_{F,m_F}$ in each hyperfine sub-state $(F, m_F)$ confined to a volume $V$ is

$$\Delta \phi = \phi_0 \sum_{F,m_F,F',m_F'} N_{F,m_F} (2F'+1)(2F+1) \left( \begin{array}{cc} F' & 1 \\ m_F & q - m_F \end{array} \right) \left( \begin{array}{cc} F & 1 \\ F' & I \end{array} \right) \frac{\Delta F_{F,F'} (\gamma/2)^2}{\Delta F_{F,F'} + (\gamma/2)^2}.$$ (1)

where $\gamma$ is the line width of the transition, $\Delta F_{F,F'}$ is the detuning of the incident light with respect to the $L_J(F) \rightarrow L'_{J'}(F')$ transition, and $\phi_0 = 3l\lambda^2(2J' + 1)/4\pi V$; the Wigner 3j and 6j symbols are defined in [18]. The atom probing light is derived from an external grating stabilized diode laser frequency locked to the atomic line. The frequency of the probe laser is $\Delta_{L5} = 160$ MHz blue detuned from the Cs D2 line $F = 4 \rightarrow F' = 5$ transition. Since the phase-shift decreases with $1/\Delta$, this probe light is only sensitive to the atomic population in the $F = 4$ state and the expression [1] reduces to (assuming $m_F = 0$ and light polarized along the quantization axis $q = 0$):

$$\Delta \phi = \frac{5}{36} \phi_0 N_{4,0} \frac{(\gamma/2)\Delta F_{F,F'}}{\Delta F_{F,F'} + (\gamma/2)^2},$$ (2)

which is the $|1\rangle$ clock state contribution to the phase shift.

Atomic probing is performed with light pulses with a typical duration of a microsecond produced with a standard acousto-optical modulator. We record the pulses in a homodyne-like setup with a low noise differential photo detector. The detector output is digitized with a high bandwidth oscilloscope and the pulse areas extracted using numerical integration. It is crucial for the minimal destructiveness of the measurement that the observed phase fluctuations of the probe light from the empty interferometer are limited by the shot noise [13]. Figure 2 shows examples of microwave

FIG. 2: (color online) Rabi oscillations (average of 10 experimental cycles) on the clock transition for an ensemble of Cs atoms (optically pumped towards the $(F = 4, m_F = 0)$ state) as inferred from the phase shift of probe laser light. The oscillations are recorded using probe pulses with a repetition period of 6 μs and duration of 0.5 μs (blue line) and 1.0 μs (red line), respectively. In the latter case a pronounced damping of oscillations is observed, however, with coherent dynamics at longer times (see inset). In the former case the fringe contrast for the normalized phase shift is limited to about 54% as result of ~30% remaining atoms in $(F = 4, m_F \neq 0)$ states.
induced Rabi-flopping between the clock states as observed with our interferometer. The probe light beam interacting with the atoms has a power of 140 nW distributed into 0.5 μs and 1.0 μs pulses for the two traces shown, respectively (corresponding to $3 \times 10^5$ and $6 \times 10^5$ photons/pulse). A marked difference in oscillation frequency and decay between the two traces can be observed as a result of the rather modest change in the probe pulse duration by a factor of two. The decay of oscillation visibility is caused by several processes. Even in the absence of the probe light a decay will be present due to dephasing between atoms caused by inhomogeneous differential light shifts from the dipole trapping laser beam and small spatial variations in the microwave driving field. The addition of probe laser light leads to a small amount of spontaneous photon scattering which can be sub-divided into inelastic Raman and elastic Rayleigh events [19]. The former leads to complete decoherence while the effect of the latter depends on the internal state of the atoms in that atomic ensembles at the poles of the Bloch sphere (i.e., all atoms in either the $|\uparrow\rangle$ or the $|\downarrow\rangle$ state) are not affected since elastic scattering takes an atom back to its original internal state. Even with the probing being close to non-destructive in the sense of little spontaneous photon scattering, the dispersive interaction (responsible for the observable phase shift of probe light) will act as to wash out Rabi oscillations as a result of a frequency shift over the sample. An ac Stark shift is imposed onto the atoms every time the probe light is applied [20] changing the phase between clock states superpositions as $|\uparrow\rangle + |\downarrow\rangle \sim |\uparrow\rangle + e^{i\phi}|\downarrow\rangle$. In our experiment the average value of $\phi$ per photon is on the order of $4 \times 10^{-7}$ rad which also characterizes the magnitude of the phase spread over the atomic ensemble as a result of the Gaussian probe beam profile. This inhomogeneous dephasing of atoms is responsible for the dramatic increase in effective Rabi frequency and envelope decay when doubling probe photon number in Fig. 2 [21]. By only applying the probe pulses every half oscillation period, in what corresponds to a spin echo sequence, the dephasing can be minimized.

As mentioned, our optical pumping scheme is not able to transfer all of the atoms to the $(F = 4, m_F = 0)$ clock state. In Fig. 2 this manifests itself as a fringe visibility limited to 54%. To purify the atomic polarization further we apply a microwave $\pi$-pulse transferring these atoms to the $(F = 3, m_F = 0) \equiv |\downarrow\rangle$ clock state and blow away the remaining atoms in the $(F = 4, m_F \neq 0)$ states using resonant light on the $6S_{1/2}(F = 4) \rightarrow 6P_{3/2}(F' = 5)$ cycling transition. In Fig. 3(a) we show Rabi oscillation as recorded for a such a purified ensemble initially in the $(F = 3, m_F = 0)$ clock state. The atoms are probed with pulses containing $\lesssim 10^6$ photons every 2.3 μs corresponding to almost 50 times per Rabi cycle. Since this is far beyond what can be resolved in the figure we include a zoom-in on the first millisecond of evolution in Fig. 3(b,c). Figure 3(b) shows a single experimental realization with clear Rabi oscillations albeit with some noise. Of course, by averaging over more experimental realizations [Fig. 3(c)] an improved signal to noise ratio is achieved. Clearly, the data presented in Fig. 3(b) demonstrates the capabilities of our method in that the coherent evolution of an ensemble can be followed “non-destructively” in “real time”.

As is well known, a two-level quantum system is formally equivalent to a spin 1/2 particle so that our phase shift measurement of the atomic ensemble can be interpreted as a collective pseudo-spin projection observation. Experimentally, we can prepare an ensemble of atoms in an equal coherent superposition of $|\uparrow\rangle$ and $|\downarrow\rangle$ by applying a microwave $\pi/2$ pulse to our atomic sample after the purification stage. It is possible to achieve a zero phase shift for such a coherent spin state (CSS) in the balanced interferometer by employing a two-color probing scheme. To determine the population in $|\uparrow\rangle$, we use an additional probe laser at $\Delta_{3,2} = -135$ MHz,
the variance of the projection subsequent measurement beyond the standard quantum limit. The quantum projection noise estimated from our experimental parameters is shown as a line. The inset shows the distribution of the measured pseudo-spin projection, its width increasing with atom number.

red detuned from the $F = 3 \rightarrow F = 2$ transition and coupled to the interferometer via the same optical fiber as the $F = 4 \rightarrow F' = 5$ probing laser. The detunings are arranged such that with equal powers of the two probes, we obtain a zero mean phase shift for equal populations in both levels, irrespectively of the number of atoms in the ensemble. Using both probe beams (colors) at the same time thus gives information on the population number difference of the two hyperfine states. It is known \[14\]\[17\] that when the probe power is increased the pseudo-spin measurements become limited by the projection noise of atoms (the quantum fluctuations of the CSS \[22\]).

In order to reach this regime we employ a single pulse with $3.6 \times 10^7$ photons roughly corresponding to the total photon number used during the entire observation cycle of Fig.3(b). Figure 4 shows the observed atomic pseudo-spin fluctuations as a function of the atom number along with an estimate of the atomic quantum projection noise. The data presented results from the analysis of $\sim 34000$ repetitions of the experimental cycle. As can be seen, for low atom numbers our measurements of the collective pseudo-spin projection show the expected quantum noise level and characteristic linear scaling of atomic noise (variance) with atom number. For higher atom numbers, however, non-quantum noise sources contribute by a non-negligible part. We attribute this to the relative amplitude and phase fluctuations of the two independent probes. Reduction of this classical (quadratic) noise component will take us to the regime where the atomic projection noise becomes comparable to the shot noise of the probe light, which would be of considerable interest since our dispersive light-atom interaction has a quantum non-demolition (QND) character \[23\].

A measurement of the collective pseudo-spin projection could hence be used to predict the outcome of a subsequent measurement beyond the standard quantum limit. Such predictive power squeezes the variance of the projection conditionally. When used in a feedback scheme the information gained in the first measurement can be used to construct unconditionally squeezed target states. Such engineered non-classical collective states open up the possibility to surpass the projection noise limit for atomic clocks operated using a Ramsey sequence as discussed in \[17\] for our experimental configuration.

In conclusion, we have measured the state dependent refractive index of a trapped ensemble of Cs atoms and shown the ability to follow coherent processes such as Rabi oscillations in “real time”. Using a shot noise limited two-color probing scheme we have measured the noise of the pseudo-spin projection of atoms in a superposition between the clock states. The recorded atomic pseudo-spin noise is near the standard quantum limit – the projection noise, indicating our ability to perform a QND measurement on cold dipole trapped atoms.

This work was funded by the Danish National Research Foundation, as well as the EU grants QAP, COVAQUAL and EMALL. N.K. acknowledges the support of the Danish National Research Council through a Steno Fellowship and helpful advise from Stefan Kuhr.

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