Nondestructive Probing of Rabi Oscillations on the Cesium Clock Transition near the Standard Quantum Limit

P. J. Windpassinger,[1] D. Oblak,[1] P. G. Petrov,[1,*] M. Kubasik,[2,1] M. Saffman,[3] C. L. Garrido Alzar,[1,†] J. Appel,[1]
J. H. Müller,[1] N. Kjærgaard,[1,‡] and E. S. Polzik[1]

[1]*QUANTOP, Niels Bohr Institute, University of Copenhagen, Denmark*
[2]*ICFO, Institut de Ciències Fotòniques, Barcelona, Spain*
[3]*Department of Physics, University of Wisconsin, Madison, Wisconsin 53706 USA*
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We report on the nondestructive 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 pseudospin 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.

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 lifetimes 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 repreparations 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 nondestructive probing could, e.g., prove advantageous to optical lattice clocks which are presently limited by the time it takes to reprepare atomic samples [10,11]. Recently, a dispersive measurement of Rabi oscillations on the cesium clock transition was demonstrated [12]. In that work Rabi flopping between the Cs clock states was observed by continuously probing the state-dependent birefringence of a cold atomic sample. The authors state that they were not able to reach the sensitivity sufficient for observation of the atomic quantum spin noise which sets the ultimate limit on sensitivity of such a measurement [13].

In this Letter, we demonstrate a measurement of Rabi oscillations and the pseudospin of the cesium clock transition which is fast, nondestructive, and allows us to approach the standard quantum limit of sensitivity. The state-dependent index of refraction of a 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 modify 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
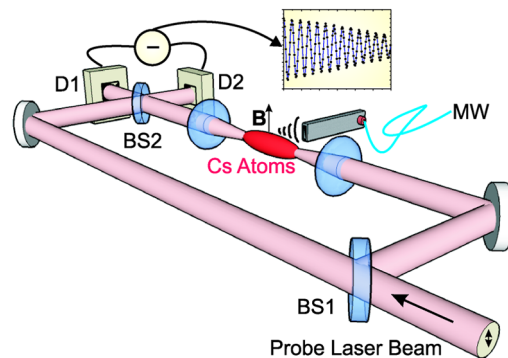

FIG. 1 (color online). Schematic drawing of the experimental setup. A probe laser beam enters the Mach-Zehnder interferometer via a port of the beam splitter BS1. One part of the beam propagates through the Cs atoms as they interact with the radiation field of the microwave source MW. The other part of the beam propagates on a reference path with no atoms. The two parts are recombined at the beam splitter BS2 and the phase shift from the atoms is detected as the differential signal of detectors D1 and D2 at the two output ports of BS2.

compared to typical dc detectors. This allows us to reduce the number of probe photons and thus to minimize the destructiveness of the atomic measurement. In particular, our detection of light is shot noise limited, which in turn allows 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 5×10^5 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 piezoactuated mirror using a weak auxiliary far off-resonance laser beam counterpropagating 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 ~ 1 G to define a quantization axis, and optically pump the atoms to the $(F = 4, m_F = 0) \equiv |\uparrow\rangle$ clock state using vertically polarized laser light driving $6S_{1/2}(F = 4, m_F \neq 0) \rightarrow 6P_{3/2}(F' = 4)$ π transitions. An additional repumping laser beam resonant with the $6S_{1/2}(F = 3) \rightarrow 6P_{3/2}(F' = 4)$ π 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 $|\uparrow\rangle$ with an efficiency likely to be limited by m_F coherences created by our narrow-bandwidth (~ 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 π 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 λ propagating a distance l through an atomic gas with population N_{F,m_F} in each hyperfine substate (F, m_F) confined to a volume V is

$$\Delta\phi = \phi_0 \sum_{F,m_F,F',m_F'} N_{F,m_F}(2F'+1)(2F+1)\underbrace{\begin{pmatrix} F' & 1 & F \\ m_F' & q & -m_F \end{pmatrix}^2}_{\text{Wigner } 3j \text{ symbol}} \underbrace{\begin{Bmatrix} J & J' & 1 \\ F' & F & I \end{Bmatrix}^2}_{\text{Wigner } 6j \text{ symbol}} \frac{(\gamma/2)\Delta_{F,F'}}{\Delta_{F,F'}^2 + (\gamma/2)^2}, \qquad (1)$$

where γ is the linewidth of the transition, $\Delta_{F,F'}$ 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 $\Delta_{4,5} = 160$ 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 $q = 0$):

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

which is the $|\uparrow\rangle$ 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 homodynelike 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 fluc-

tuations of the probe light from the empty interferometer are limited by the shot noise [15].

Figure 2 shows examples of microwave 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 and 1.0 μs pulses for the two traces shown, respectively (corresponding to 3×10^5 and 6×10^5 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 2. 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 subdivided 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 nondestructive in the sense of little
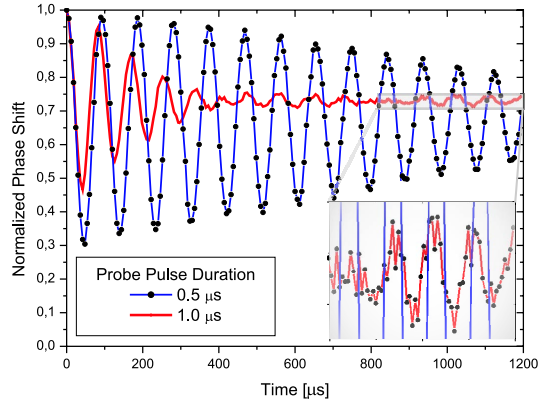
FIG. 2 (color online).   Rabi oscillations (average of 10 experimental cycles) on the clock transition for an ensemble of Cs atoms [optically pumped towards the $(F = 4, m_F = 0)$ state] as inferred from the phase shift of probe laser light. The oscillations are recorded using probe pulses with a repetition period of 6 μs and duration of 0.5 and 1.0 μs, 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 $\sim$30% remaining atoms in $(F = 4, m_F \neq 0)$ states.

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 $|\downarrow\rangle + |\uparrow\rangle \curvearrowright |\downarrow\rangle + e^{i\phi}|\uparrow\rangle$. In our experiment the average value of ϕ per photon is on the order of 4×10^{-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 the 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 π-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 oscillations as recorded for such a purified ensemble initially in the $(F = 3, m_F = 0)$ clock state. The atoms are probed with pulses containing $\lesssim 10^5$ 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 Figs. 3(b) and 3(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) demonstrate the capabilities of our method in that the coherent evolution of an ensemble can be followed "nondestructively" 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 pseudospin 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 $|\downarrow\rangle$, we use an additional probe laser at $\Delta_{3,2} = -135$ MHz, 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
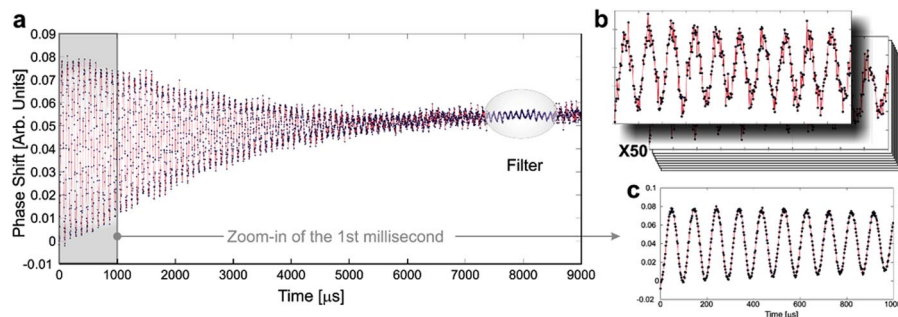

FIG. 3 (color online).   Purified sample of atoms (a) Rabi cycling on the clock transition recorded using 0.2 μs probe pulses with a repetition period of 2.3 μs. Oscillations are still visible after a time of 8 ms (a running average filter over 8 pulses has been included at this point of time to enhance the oscillations) corresponding to having applied $\sim$3500 probe pulses. The trace is an average of 50 realizations of the experiment. (b) A single experiment recording of Rabi oscillations during the first millisecond. (c) A zoom-in on the first millisecond of the trace in (a), i.e., an average of 50 traces as shown in (b). At time 0 ms the phase shift is zero as a result of all the atoms being transferred to the $(F = 3, m_F = 0)$ clock state and the probe only being sensitive to atoms in the $F = 4$ states.
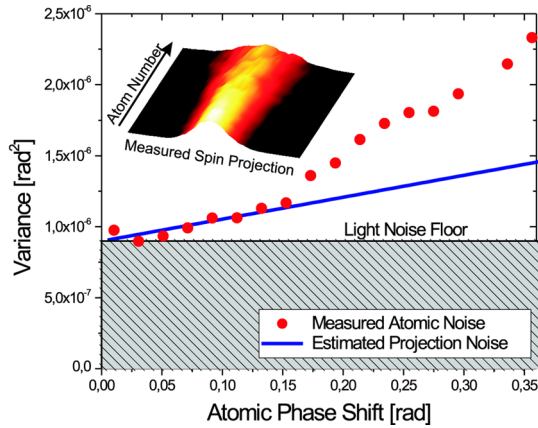
FIG. 4 (color online). The fluctuations in the interferometer phase for ensembles in an equal superposition of the clock states as a function of the interferometer phase shift with all atoms at a pole of the Bloch sphere (this phase shift is proportional to the atom number). The quantum projection noise estimated from our experimental parameters is shown as a line. The inset shows the distribution of the measured pseudospin projection, its width increasing with atom number.

equal powers of the two probes, we obtain a zero mean phase shift for equal populations in both levels, irrespective 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 pseudospin 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 3.6×10^7 photons, roughly corresponding to the total photon number used during the entire observation cycle of Fig. 3(b). Figure 4 shows the observed atomic pseudospin 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 $\sim 34\,000$ repetitions of the experimental cycle. As can be seen, for low atom numbers our measurements of the collective pseudospin projection show the expected quantum noise level and characteristic linear scaling of atomic noise (variance) with atom number. For higher atom numbers, however, nonquantum 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 nondemolition (QND) character [23]. A measurement of the collective pseudospin 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 condition-

ally. When used in a feedback scheme the information gained in the first measurement can be used to construct unconditionally squeezed target states. Such engineered nonclassical 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 pseudospin projection of atoms in a superposition between the clock states. The recorded atomic pseudospin noise is near the standard quantum limit—the projection noise, indicating our ability to perform a QND measurement on cold dipole-trapped atoms.

*Present address: Department of Physics, Ben Gurion University, Be'er-Sheva 84105, Israel.
†Present address: LCF, Institut d'Optique, 91127 Palaiseau, France.
‡niels.kjaergaard@nbi.dk
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