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Observation of ground-state Ramsey fringes

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We have used trapped ^{85}Rb atoms to demonstrate an atom interferometric measurement of atomic recoil in the frequency domain. The measurement uses echo techniques to generate a Ramsey fringe pattern. The pattern exhibits recoil components consistent with theoretical predictions. We find the measurement to be insensitive to magnetic field gradients and discuss the prospects for a precision measurement of the recoil frequency.

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I. INTRODUCTION

During the past 15 years, there have been rapid advances in the field of precision measurements in atomic physics. These developments have been stimulated by the ability to obtain ultracold samples of trapped atoms using laser cooling techniques [1,2]. The robust nature of these traps has led to atomic fountain clocks that now serve as time standards [3,4] and improved measurements of atomic structure [5–7]. Atom interferometers (AI's) using cold atoms have achieved state of the art measurements of gravitational acceleration [8,9] and rotation [10]. AI's have also been used for precise measurements of the atomic fine-structure constant α [11]. This constitutes a particularly interesting test of fundamental physics [12]. AI's are sensitive to the momentum transfer $\overrightarrow{\Delta k}$ from laser fields to the atom, and can be used to obtain a precise value for the atomic recoil frequency $\omega_r = \hbar(\Delta k)^2/2m_{atom}$. Recently, it has become possible to measure the wave vector of the laser field k, as well as the Rydberg constant, the proton-electron mass ratio, and atomic mass with unprecedented accuracy [13–16]. It has, therefore [12], become feasible to obtain an improved value for α at the level of ~ 1 part per 10^9, which can surpass the precision of the measurement based on the electron g factor [17].

The best atom interferometric measurements of h/m_{atom} have involved Raman transitions between hyperfine ground states of cesium atoms [11]. However, the sensitivity to a number of systematic effects such as frequency stability between the two lasers used to couple the ground states, differential ac-Stark shifts associated with the ground states, and dependence on stray electric and magnetic fields, must be studied in detail as in Ref. [9] before a final measurement can be reported. A measurement of the recoil frequency using a time domain AI was demonstrated in Ref. [18], which is potentially insensitive to several of these systematic effects. Here, the cold atoms are manipulated in the same internal ground state using off-resonant standing-wave pulses. Here, only a single laser is required to produce the excitation and detection pulses. There is no necessity to optically pump the sample or use magnetic shielding. These features reduce experimental complexity. There has also been a continued interest in using such single-state AI's for a measurement of h/m_{Rb} following recent experiments in Bose condensed samples [19] using a technique similar to Ref. [18].

A new scheme that also uses atoms in the same internal state but works in the frequency domain was proposed in Ref. [20]. In this work, we have utilized this scheme to obtain a preliminary measurement of ω_r using laser cooled Rb atoms [21]. As in Ref. [3,8,11], the degree of precision is limited mainly by the transit time of ground-state atoms through the region of interaction.

II. SINGLE-STATE AI'S

For the AI in Ref. [18], atoms in a single hyperfine ground state are diffracted into a superposition of momentum states separated by multiples of $2\hbar k$ using a standing-wave pulse detuned from the excited state and applied at $t=0$. The standing-wave interaction produces a spatially periodic density (grating) in the sample. This grating has a period of $\lambda/2$, where, λ is the wavelength of light. Although the grating decays due to the velocity distribution of the sample, it can be rephased by a second off-resonant standing-wave pulse (applied at $t=T$) in a manner reminiscent of a photon echo. The AI thus relies on the discrete nature of atomic recoil (due to absorption and stimulated emission of photons between the traveling wave components of the standing wave) and matter wave interference between different center-of-mass momentum states. In this case, the rephased density grating (echo) is produced in the vicinity of $t=2T$. The echo is detected using a heterodyne technique by coherently backscattering a traveling-wave (readout) pulse from the sample. In this case, the shape of the echo signal is given by

$$S_0(t)=(t-2T)e^{-[(t-2T)\Delta k u/2]^2}, \tag{1}$$

where u is the most probable speed. For a two-level atom, the periodic dependence of the backscattered signal on the pulse separation T is given by

$$S_1 \approx J_2(2\theta_2 \sin(\omega_r T)). \tag{2}$$

The argument of the Bessel function contains the pulse area of the second standing-wave pulse $\theta_2=\int_0^\tau \Omega(t)dt$, where Ω is the light shift due to the atom field interaction integrated over the pulse width τ. In Ref. [18], the predicted dependence of the signal on T was verified. A precise $(\sim 1/10^4)$ measurement of ω_r was obtained by measuring the amplitude of the signal as a function of T and measuring the time between well-displaced zeros. An important advantage of this method is that the phase of the scattered signal is not essential for the recoil measurement.

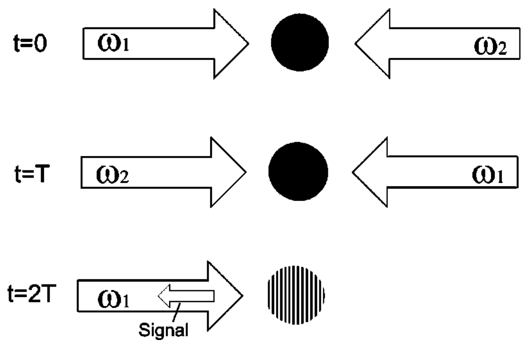

FIG. 1. Schematic diagram of pulsed laser fields used in the experiment.

In this work, we have followed the proposal outlined in Ref. [20] and measured ω_r in the frequency domain. Two off-resonant, counterpropagating traveling-wave pulses with optical frequencies ω_1 and ω_2 are used to drive transitions between the same atomic hyperfine ground state at $t=0$. The sample is excited after a time T by a second set of traveling-wave pulses. However, the directions of the second set of pulses are reversed as shown in Fig. 1.

The grating is detected near $t=2T$ by scattering an off-resonant (readout) traveling wave with frequency ω_1 from the sample and measuring the amplitude and phase of the scattered light at frequency ω_2. This excitation scheme is similar to a Ramsey fringe experiment [5,11,22–24] in which the population or coherence associated with an atomic level acquires an oscillatory phase that depends on the detuning, $\delta=\omega_1-\omega_2$. In our case, the ground-state population grating acquires a Ramsey phase $\phi=4\delta T$ and is used as a probe of this phase. Reversing the directions of the second set of excitation pulses results in a cancellation of the Doppler phase associated with the momentum states at the echo point and a preservation of the Ramsey phase. We can express the backscattered signal as [20]

$$S(\delta,T)=\exp(4i\delta T)J_2[2\theta_2\sin(\omega_r T)]. \tag{3}$$

The complex exponential in Eq. (3) makes it necessary to measure the phase of the signal in order to observe the effect of recoil.

In atomic beam experiments [25], the oscillatory fields are separated spatially. The longitudinal velocity distribution causes each velocity class to interact with laser fields with a different time separation T. In such an experiment, the observed signal represents an average over the entire velocity distribution and this causes the Ramsey fringes to be observed. In experiments involving cold atoms, the fields are provided by laser pulses. As a consequence, the time separation experienced by the entire sample is the same. It is, therefore, necessary to repeat the experiment for a range of values T, and average the results to obtain the Ramsey line shape [26].

Equation (3) predicts a characteristic Ramsey fringe pattern with recoil components at $\delta=0,\pm0.5\omega_r,\pm\omega_r,\ldots$. The precision of the measurement of ω_r depends on the precision to which δ is known. Both this work and Ref. [18] are done in the Raman-Nath regime, with pulses $<1\ \mu$s. Nevertheless, there is an uncertainty about the definition of T in Eq. (2). This uncertainty is avoided in this work since we average over a range of T in Eq. (3). However, the ultimate precision of both experiments is determined by the stability of a frequency standard. In the time domain experiment, the frequency standard would control the time base of the experiment. In the frequency domain, the frequency standard controls the oscillators used to generate the frequency difference.

In previous Ramsey experiments [5,22–24], the precision that can be achieved depends on a precise determination of the detuning between the laser and the excited state and is limited by the lifetime of the excited state and the laser linewidth. In contrast, our experiment involves excitation to a virtual transition and stimulated emission back to the ground state. In this case, the detuning $\delta=\omega_1-\omega_2$ can be easily controlled with a precision determined by a frequency standard. Since our beams are generated from a single laser, variations in laser frequency are common to both beams and a laser with an ultranarrow line width is not required as in atomic clock experiments [5,22–24]. The precision is limited only by the transit time of ground-state atoms rather than the excited-state lifetime (in practice, the effective transit time is limited by collisions and stray light fields). We also note that in this case the range of δ ($\sim$10 MHz) is limited by the pulse bandwidth.

III. EXPERIMENTAL DETAILS

We have used a sample of ^{85}Rb atoms trapped in a magneto-optical trap (MOT). Our sample contains $\sim10^8$ atoms at a temperature of $\sim$200 μK. The trapping beams and excitation beams are derived from the same cw laser. The amplitude and frequency of these beams are controlled by a chain of acousto-optic modulators (AOMs). The pulses used for atom interferometry are tuned $\sim$90 MHz above the $F=3\rightarrow F=4'$ transition. The AOMs are driven by oscillators that are phase locked to a commercially available Rb frequency standard with a short term stability of 0.5 mHz. The oscillators operate near 250 MHz and the frequency difference $f=(\omega_1-\omega_2)/2\pi$ can be adjusted to within 10 mHz. We measure and correct the phase of the rf oscillators so that it is constant at the time of the readout pulse. Since the atomic wave function picks up a spatial and temporal phase from each of the interaction pulses, the signal can be predicted to vary as $e^{[-i\delta(t_1+2t_2+t)]}$ [27]. For our conditions, $t_1=-2T, t_2=-T$, and $t=0$ define the pulse sequence. The time separation T between pulses can be controlled to within 5 ps by delay generators. The time base of the generators is also slaved to the Rb standard.

The experiment is typically carried out at a repetition rate of 10 Hz. The measurement is done with the trapping beam and magnetic-field gradient turned off. The first excitation pulse is applied $\sim$1 ms after the turnoff of the trapping laser and magnetic-field gradient. The repetition rate is limited by the time required to turn on the magnetic-field gradient.

We use a balanced heterodyne detection system similar to Ref. [18] for detecting the echo, as shown in Fig. 2.

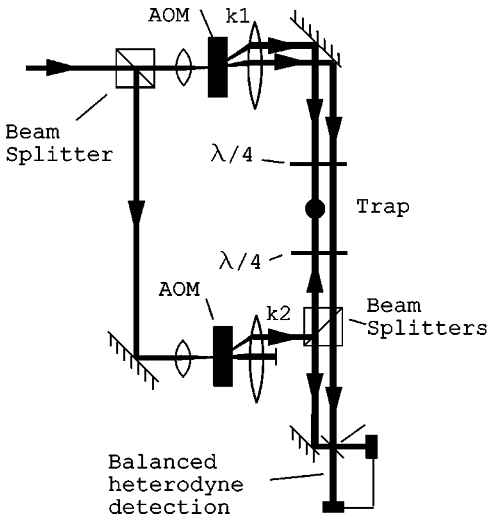

FIG. 2. Experimental setup; 1/4 wave plates are used to produce circularly polarized excitation pulses.

The undiffracted beam from AOM1 is used as a local oscillator. When the readout pulse is applied just before $t = 2T$, the backscattered echo signal is observed on both channels of the detection system. We treat these signals as the real and imaginary components of the scattered light and use them to obtain the amplitude and phase of the signal.

IV. RESULTS AND DISCUSSION

Figure 3 shows a component of the echo signal as a function of time.

The shape of the signal is consistent with Eq. (1). We integrate the first half of the echo ($\sim$800 ns before the zero crossing) and subtract the integral of the second half to obtain the amplitude of a component. This amplitude is measured as a function of detuning δ for a fixed T. Figure 4 shows the amplitude as a function of the detuning δ for $T = 100\ \mu$s.

The amplitude of the signal has an oscillatory dependence on δ given by $S_0 = \cos(4\delta T)$ as seen from the fit in Fig. 4. For a fixed value of T, we obtain the average values of the frequencies of the real and imaginary components of the echo signal. This measurement is repeated for different time separations, T. A linear fit of the measured period as a function of T gives a slope of 4.004 and an offset of 0.7 μs. We

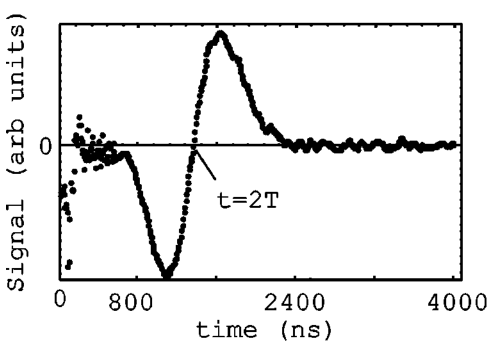

FIG. 3. Echo as a function of time.

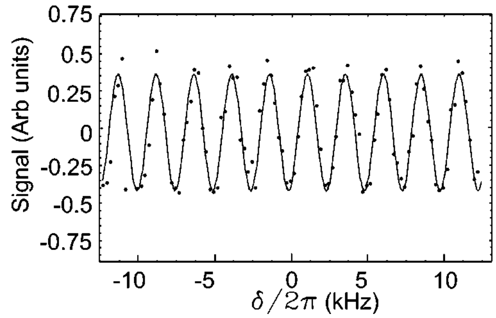

FIG. 4. Oscillation of a component of the echo signal as a function of detuning δ for $T = 100\ \mu$s; data are fit to the form $\cos(4\delta T)$ and shown as the solid line; the fit gives a period of 2.50 kHz.

note that the slope is in agreement with Eq. (3). The Ramsey fringe pattern is then obtained by averaging a particular component (real or imaginary) of the oscillatory signal over a range of T. The amplitude of the echo as a function of T in Eq. (2) is fit to a decaying exponential. The amplitudes of the oscillatory signals are then weighted to compensate for the decay. Figure 5 shows the Ramsey fringe pattern observed over the range $T = 12$–$164\ \mu$s by varying T in steps of 4 μs. A least-squares fit to Eq. (3) with ω_r and θ_2 as free parameters is shown as a dashed line in Fig. 5.

The fit yields $\omega_r = 97.0 \times 10^3\ \mathrm{s}^{-1}$. This is consistent with $\omega_r = \hbar \Delta k^2 / 2m_{\mathrm{Rb}}$, where $\Delta k = 2k$. The data show peaks at $\pm 0.5\omega_r$ and $\pm \omega_r$, which is consistent with Eq. (3). We also note that the fit gives $\theta_2 = 1.8$ which is in reasonable agreement with experimental parameters. Analysis of the residuals currently allows us to determine ω_r with a precision of $\sim 1/10^3$. The relative amplitudes of the observed recoil components and their signs are consistent with predictions for this pulse area [20]. An interesting feature of this experiment is that the center of the fringe pattern has to occur at $\delta = 0$ as shown in Fig. 5. This peak corresponds to the undiffracted component of the signal. We have also been able to demonstrate the insensitivity of our measurement to magnetic-field gradients. When the measurement is conducted with or without the magnetic-field gradient associated with the MOT, there is no apparent difference in the observed signal. This adds to experimental convenience, since it is possible to acquire data without pulsing the magnetic-field gradient. We

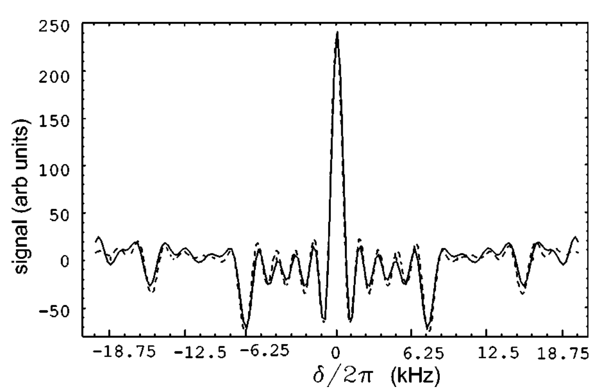

FIG. 5. Observed Ramsey fringe pattern; solid line is data; dashed line is fit which yields $\omega_r = 97.0 \times 10^3\ \mathrm{s}^{-1}$ and $\theta_2 = 1.8$.

have also measured the Ramsey phase in the time domain by using a fixed δ and varying T. We find that the signal has the same dependence on the Ramsey phase as in the frequency domain experiment.

V. CONCLUSIONS

Since we rely on the stability of a commonly available frequency standard, our precision is expected to be limited only by the transit time of the atoms. In this work, the transit time is ~ 200 μs due to decoherence effects of collisions and scattered light. Since we can control δ to <10 mHz, we estimate the resolution $\omega_r / \Delta\omega_r$ to be $\sim 8 \times 10^5$. By modifying our vacuum system and employing mechanical shutters we have achieved a transit time of ~ 5 ms (the theoretical value of the transit time depends on the beam diameter and cloud temperature and is estimated to be ~ 15 ms for our conditions [28]). Analysis of the width of the Ramsey fringes shows that the fringe width should scale as $\sim 1/T$. It is also possible to achieve a substantial increase in the measurement accuracy by measuring the separation between widely spaced higher-order recoil components. This would require using a higher pulse area θ_2 as suggested by Ref. [20]. We, therefore, estimate the precision to be $\sim 1/10^6$ at the transit-time limit. At this level, we expect to do more extensive tests of systematic effects associated with ac-Stark shifts, magnetic fields and field gradients, the quality of laser beam profiles, and vibrations. For small echo amplitudes, it is possible that the frequency domain technique may result in better signal-to-noise than the time domain measurement. This is because the amplitude and phase of each frequency component can be accurately determined by fitting several periods of the oscillatory signal. Another desirable feature of this technique is that the shift in the position of the central Ramsey fringe (with excitation pulses along the vertical) can be used for an accurate measurement of gravity [20].

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[1] E.L. Raab *et al.*, Phys. Rev. Lett. **59**, 2631 (1987).
[2] C. Monroe *et al.*, Phys. Rev. Lett. **65**, 1571 (1990).
[3] C. Fertig and K. Gibble, Phys. Rev. Lett. **85**, 1622 (2000), and references therein.
[4] G. Santarelli *et al.*, Phys. Rev. Lett. **82**, 4619 (1999).
[5] K. Sengstock *et al.*, Opt. Commun. **103**, 73 (1993).
[6] Th. Kisters *et al.*, Appl. Phys. B: Lasers Opt. **59**, 89 (1994).
[7] C.W. Oates *et al.*, Phys. Rev. Lett. **76**, 2866 (1996).
[8] M. Kasevich and S. Chu, Phys. Rev. Lett. **67**, 181 (1991).
[9] A. Peters *et al.*, Nature (London) **400**, 849 (1999).
[10] T.L. Gustavson *et al.*, Phys. Rev. Lett. **78**, 2046 (1997).
[11] D.S. Weiss *et al.*, Phys. Rev. Lett. **70**, 2706 (1993).
[12] B. Taylor, Metrologia **31**, 181 (1994).
[13] Th. Udem *et al.*, Phys. Rev. Lett. **82**, 3568 (1999).
[14] Th. Udem *et al.*, Phys. Rev. Lett. **79**, 2646 (1997).
[15] D.L. Farnham *et al.*, Phys. Rev. Lett. **75**, 3598 (1995).
[16] M.P. Bradley *et al.*, Phys. Rev. Lett. **83**, 4510 (1999).
[17] R.S. VanDyck, Jr. *et al.*, Phys. Rev. Lett. **59**, 26 (1987).
[18] S.B. Cahn *et al.*, Phys. Rev. Lett. **79**, 784 (1997).
[19] S. Gupta *et al.*, Phys. Rev. Lett. **89**, 140401 (2002).
[20] B. Dubetsky *et al.*, Phys. Rev. A **56**, R1091 (1997).
[21] M. Weel *et al.*, in *Proceedings of the XVIII International Conference on Atomic Physics*, edited by H. Sadeghpour, D.E. Pritchard, and E.J. Heller (World Scientific, Singapore, 2002), p. 192.
[22] J.C. Bergquist *et al.*, Phys. Rev. Lett. **38**, 159 (1977).
[23] F. Ruschewitz *et al.*, Phys. Rev. Lett. **80**, 3173 (1998).
[24] R.L. Barger *et al.*, Appl. Phys. Lett. **34**, 850 (1979).
[25] Ch.J. Bordé *et al.*, Phys. Rev. A **30**, 1836 (1984).
[26] L.S. Vasilenko *et al.*, Opt. Commun. **53**, 371 (1985).
[27] P. Berman (private communication).
[28] I. Yavin *et al.*, Am. J. Phys. **70**, 149 (2002).