Suspension of Atoms Using Optical Pulses, and Application to Gravimetry

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Atoms from a ^{87}Rb condensate are suspended against gravity using repeated reflections from a pulsed optical standing wave. Up to 100 reflections are observed, yielding suspension times of over 100 ms. The local gravitational acceleration can be determined from the pulse rate required to achieve suspension. Further, a gravitationally sensitive atom interferometer was implemented using the suspended atoms. This technique could potentially provide a precision measurement of gravity without requiring the atoms to fall a large distance.

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Many experiments using ultracold atoms rely on magnetic and/or optical fields for confinement, as these techniques permit atoms to be studied and manipulated over time scales of many seconds. However, the confinement forces affect the atomic wave function in a way that is generally difficult to determine precisely. One might, for example, propose to measure the local gravitational acceleration g by determining the magnetic field gradient required to keep an atom suspended. Unfortunately, there is no practical way to measure the applied gradient with sufficient accuracy to make this method useful. In contrast, using freely falling atoms, gravity can be measured very accurately through atom interferometry [1,2]. To obtain high precision, however, long interaction times are needed. The resulting vertical space requirement limits the performance achievable in volume-constrained applications such as inertial navigation.

In this Letter, we demonstrate a method for suspending atoms that is sufficiently precise to use in gravimetry and other experiments. The atoms repeatedly interact with an optical standing wave that provides quantized and well-characterized momentum kicks. Effectively, the atoms "bounce" off the light field. A similar idea was recently proposed by Impens *et al.* [3]. We also demonstrate a gravity-sensitive interferometer using the confined atoms. Although we do not achieve significant precision here, improvements may permit measurements comparable to those obtained using falling atoms, but with negligible drop distance needed.

Atoms have previously been suspended by bouncing from evanescent waves [4], magnetized surfaces [5], light sheets [6], and magnetic fields [7]. However, these techniques introduce uncontrolled forces that can spoil many precision measurements. Furthermore, they have been limited to only a few bounces, while we observe up to 100. Our method is related to Bloch oscillations of atoms held in a static standing-wave potential [8,9], which may also prove useful for gravimetry [10]. We compare these methods below. The controlled exchange of multiple photon recoils is also related to experiments such as [11], in which up to $24\hbar k$ transfer was achieved in a single pulse. In comparison, we transfer up to $200\hbar k$ over the course of many pulses.

The manipulation of atoms by an off-resonant standing-wave laser was first used in thermal atomic beams [12,13]. Through the ac Stark effect, the laser induces a periodic potential that acts as a diffraction grating for the atomic wave function, producing coupling between momentum components that differ by $2\hbar k$ for light wave number k. By controlling the intensity and duration of the applied pulse, various beam-splitting and reflecting operations can be achieved. Generally the results are sensitive to the initial velocity of the atoms, but the low velocity spread in an ultracold sample allows the operations to be quite precise [14–16].

We define an order-n reflection as the operation $|n\hbar k\rangle \leftrightarrow |-n\hbar k\rangle$, where $|p\rangle$ denotes a momentum eigenstate. Suspension of atoms starts with mass m atoms held in a conventional trap. The trap is then switched off, allowing the atoms to fall. After time $t_n \equiv n\hbar k/mg$, the atomic momentum will be $-n\hbar k$ and a reflection operation is applied using a vertically oriented laser beam, resulting in $p \rightarrow +n\hbar k$. The atoms move ballistically for time $2t_n$, after which they again have $p = -n\hbar k$ and the reflection can be repeated. We implemented both order-1 and order-2 reflections, with trajectories illustrated in Fig. 1(a) and 1(b), respectively.

Losses during the reflection operation will limit the number of bounces that can be achieved. We found that performance could be improved by using compound sequences rather than single pulses. To model the operation, we numerically solved the Schrödinger equation using the Bloch expansion

$$\psi(z,t) = \sum_n c_n(t) e^{i(2nk+\delta)z} \quad (1)$$

for optical potential $V_L(z,t) = \hbar\beta(t)\cos(2kz)$. Here ψ is the atomic wave function, δ accounts for an initial momentum offset, and $\beta(t)$ is proportional to the light intensity. This yields a set of equations

$$i\frac{dc_n}{dt} = \frac{\hbar}{2m}(2nk+\delta)^2 c_n + \frac{\beta}{2}(c_{n-1} + c_{n+1}), \quad (2)$$

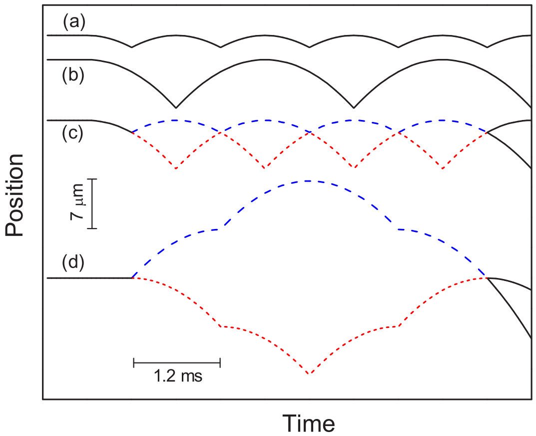

FIG. 1 (color online). Atom trajectories discussed in this Letter, shown with a common scale as indicated. (a) Bouncing atoms using order-1 reflections. (b) Bouncing atoms using order-2 reflections. (c) Interferometer produced with a combination of order-1 and order-2 reflections. Here the colored dashed curves show the two arms of the interferometer, and there are two possible output states. (d) More complex interferometer with large arm spacing. Trajectories (a)–(c) were implemented here.

which were truncated at $n = \pm 6$. For $\beta(t)$, we considered a symmetric sequence of three pulses with durations (T_1, T_2, T_1) and intensities $(\beta_1, \beta_2, \beta_1)$. The T_i's and β_i's were optimized numerically. For the order-1 reflection, we found $(T_1, T_2) = (0.355, 0.592)\omega_r^{-1}$, and $(\beta_1, \beta_2) = (1.73, 3.45)\omega_r$, where $\omega_r = \hbar k^2/(2m) \approx 2.36 \times 10^4\ \mathrm{s}^{-1}$ is the atomic recoil frequency. For order-2, we obtained $(T_1, T_2) = (0.256, 1.46)\omega_r^{-1}$ and $(\beta_1, \beta_2) = (2.28, 4.59)\omega_r$. In both cases, the calculated loss was below 2×10^{-4}, but this did not include losses due to spontaneous emission. Maintaining an error below 5×10^{-3} required $\delta/k < 0.05$ for order-1 operations and 0.02 for order-2.

Bouncing was implemented using approximately 10^4 ^{87}Rb atoms from a Bose-Einstein condensate. The atoms were prepared in the $|F = 2, m_F = 2\rangle$ ground state in a magnetic trap with oscillation frequencies $(\omega_x, \omega_y, \omega_z) = 2\pi(7.4, 0.8, 4.3)$ Hz, for z vertical. For ^{87}Rb, the photon recoil velocity $v_r = \hbar k/m$ is 5.88 mm/s and the fall time $t_1 = v_r/g$ is 0.6 ms. We drop the atoms by turning off the trap current. The current decay is nonexponential, but reaches $1/e$ of its initial value after 160 μs with repeatability better than 1 μs. Because of the finite turn-off time, the atoms take longer than time t_1 to reach a momentum of $-\hbar k$, and we compensate for this by delaying the first reflection pulse.

The standing wave was produced by a homebuilt diode laser with a wavelength of 780.193 nm, 27 GHz blue of the $5S_{1/2} \leftrightarrow 5P_{3/2}$ laser cooling transition. An acousto-optic modulator was used to control the optical intensity. The light was then coupled into a single-mode fiber, which provided spatial filtering and pointing stability. The output from the fiber passed vertically through the vacuum cell and was retroreflected from an external mirror to produce the standing wave. At this detuning, the expected loss due to spontaneous emission is 7×10^{-4} for order-1 and 2×10^{-3} for order-2 reflections. The beam was approximately Gaussian with a waist of 1 mm.

We investigated suspension by releasing the atoms and then applying a sequence of reflection operations. The time before the first pulse and the time between pulses were varied to maximize the number of atoms remaining. The final number of atoms and their momentum state was monitored using time-of-flight absorption imaging with a resonant probe traveling along the horizontal y axis. The results for both order-1 and order-2 bouncing are shown in Fig. 2. In both cases, suspension times exceeding 100 ms were observed.

We observe a nonexponential decay of the atom number, with larger losses for the later operations. The form of this falloff varied from day to day, but the time scale was consistent. The reason for the decay is not clear, but a few possibilities can be suggested. For instance, if the pulse rate is incorrect, then the momentum error $\hbar\delta$ will increase over time, leading to greater loss. Also, the condensate expands considerably during the experiment, so if the standing-wave intensity is nonuniform, spatially dependent errors in β will develop. We plan to investigate these issues further, since our model suggests thousands of bounces should be possible.

This experiment already provides a measurement of gravity, since the optimum pulse rate depends on the value of g [3]. For the data shown, we used $t_1 = 603.0 \pm 0.5\ \mu$s, where the uncertainty is determined as the variation needed to reduce the atom number by roughly a factor of 2. This gives $g = (\hbar k)/(m t_1) = 9.759 \pm 0.008\ \mathrm{m/s^2}$, different from the expected value of $9.81\ \mathrm{m/s^2}$. Since the atoms are in a state with nonzero magnetic moment, the discrepancy can be explained by a modest ambient magnetic field gradient. Measurements outside the vacuum cell indicated a vertical gradient of $B' = 7 \pm 2$ G/m. We were able to

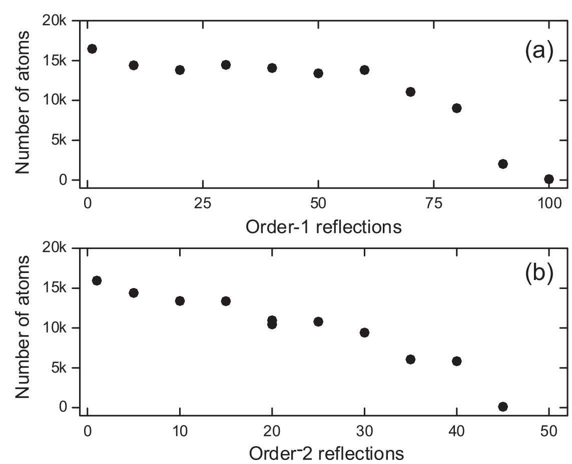

FIG. 2. Suspension of atoms using (a) order-1 and (b) order-2 reflection operations. Data points indicated the number of atoms remaining after the indicated number of reflections. In both cases, the horizontal scale corresponds to a total time of 125 ms.

determine the gradient more precisely by modifying the trap turn-off procedure to be nonadiabatic for the atomic spins, so that multiple Zeeman states were populated. As the atoms bounced, the magnetic force caused the states to separate, as in a Stern-Gerlach experiment. The separation was observed in the absorption images, and from it we obtain a value of $B' = 8.6 \pm 0.1$ G/m. This gives a corrected value for g of 9.814 ± 0.008 m/s^2. We note that magnetic gradiometry is another potential application for the suspension technique.

A more precise determination of g can be made by implementing an atom interferometer using the suspended atoms. One approach is illustrated in Fig. 1(c). The atoms are dropped as before, but at time t_1 when $p = -\hbar k$, the beam-splitting operation $|-\hbar k\rangle \rightarrow \frac{1}{\sqrt{2}}(|-\hbar k\rangle - i|+\hbar k\rangle)$ is applied, using a single optical pulse with $\beta = 1.95\omega_r$ and duration $0.145\omega_r^{-1}$. The two resulting wave packets are then independently suspended using alternating order-1 and order-2 reflections, as shown. (The order-2 reflection does not change the momentum of atoms with $p = 0$.) Eventually, the packets can be recombined, with a result that depends on their phase difference. Since one packet is always above the other, it is clear that the phase difference depends on g.

We calculate the phase difference between the packets using the quantum-mechanical solution for a falling plane wave state. A packet initially described by a wave function $\psi(z) = \exp(iqz)$ will evolve to $\psi(z, t) = \exp[i(q - \gamma t)z]\exp[i\Theta(q, t)]$ for $\gamma \equiv mg/\hbar$ and

$$\Theta(q, t) = \frac{\hbar}{2m}\left(q^2 t - q\gamma t^2 + \frac{1}{3}\gamma^2 t^3\right). \quad (3)$$

This can be verified by substitution into Schrödinger's equation. The phase difference developed during one cycle of the interferometer can therefore be expressed as

$$\Phi = \Theta(k + \delta, 2\tau) - \Theta(-k + \delta, \tau) - \Theta(3k - \gamma\tau + \delta, \tau) + \phi_{r2} + \phi_{r1}, \quad (4)$$

where $\hbar\delta$ is the momentum offset at the start of the cycle, 2τ is the cycle duration, and ϕ_{rn} is the phase difference imparted by an order-n reflection. After the cycle, the momentum offset is $\delta - 2k + 2\gamma\tau$. Evaluation of (4) yields

$$\Phi = \frac{\hbar k}{m}(-4k\tau + 2\gamma\tau^2) + \phi_{r1} + \phi_{r2}. \quad (5)$$

Thus, after N cycles, the wave function will be

$$\psi = |\hbar(k + \delta_N)\rangle - ie^{iN\Phi}|\hbar(-k + \delta_N)\rangle \quad (6)$$

for final momentum offset $\hbar\delta_N$. The beam-splitting operation is then applied with shifted phase ϕ_s, resulting in a fraction of atoms $f_+ = \sin^2[(N\Phi + \phi_s)/2]$ with momentum $+\hbar k$. We vary ϕ_s by changing the frequency of the standing-wave laser before the final beam splitter, as in [17]. By plotting f_+ vs ϕ_s, the phase $N\Phi$ is determined for various numbers of cycles, as seen in Fig. 3. We find $\Phi = 2\pi j - 0.035 \pm 0.003$ for integer j. The value of g obtained from the bouncing experiments fixes $j = -9$.

The accuracy of the data is limited by deviations from the expected linear dependence on N, as seen in the residuals in Fig. 3. We attribute the structure to residual oscillations in the magnetic field after turning off the trap. The signal corresponds to a decaying gradient with initial amplitude 10 G/m, about 0.3% of the original trap gradient. Eliminating this field might prove difficult, but its effects could be reduced by transferring the atoms to a magnetically insensitive state.

To obtain a value for g, the reflection phases ϕ_{r1} and ϕ_{r2} must be determined from the model. To do so accurately, the effect of gravity during the pulse should be included. This is accomplished by working in the interaction picture with respect to the gravitational interaction mgz. The calculation proceeds as in Eq. (2), but using the interaction Hamiltonian

$$H_I(t) = U_0^\dagger(t)V_L(z, t)U_0(t), \quad (7)$$

where $U_0(t)|q\rangle = \exp[i\Theta(q, t)]|q - \gamma t\rangle$. We reference t to the beginning of the pulse for the initial beam-splitter operation, to the center of the reflection sequences, and to the end of the recombination pulse. The cycle time τ is defined accordingly. We obtain $\phi_{r1} = (1 \pm 1) \times 10^{-2}$ and $\phi_{r2} = 0.56 \pm 0.16$. These uncertainties are the dominant source of error in the experiment. They arise primarily from a sensitivity of the phase to the intensity of the standing wave, which is difficult to control precisely. We

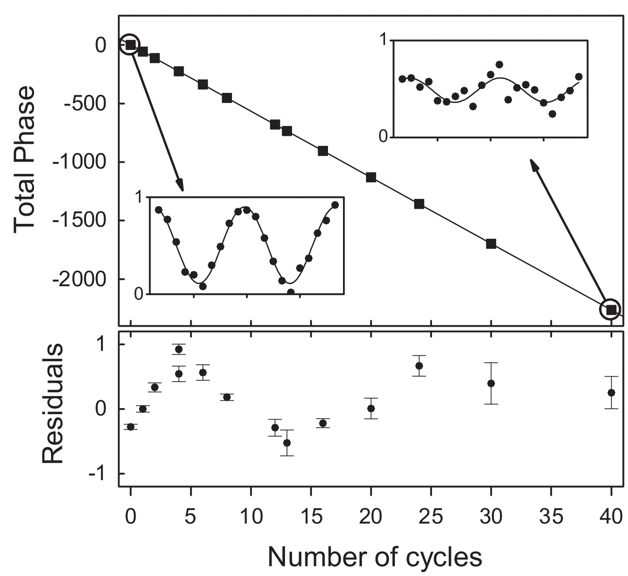

FIG. 3. Results of interferometer experiment. The upper graph shows the total phase shift observed in the output, in radians. The insets are sample plots of the fraction f_+ of atoms with $p = \hbar k$ exiting the interferometer. The cases of one cycle and 40 cycles are shown. The duration of one cycle is 2.4 ms. The residuals plotted in the lower graph are the difference between the measured phase and the linear fit; the oscillations are attributed to a transient magnetic field produced when the trap is turned off.

obtain a value for g of $9.745 \pm 0.027\ \mathrm{m/s^2}$, actually less precise than that obtained from bouncing. However, if the reflection phase errors were eliminated, the fractional uncertainty would be reduced to 5×10^{-5}.

The sensitivity to the standing-wave intensity comes from a lack of symmetry between the two arms, since the lower arm undergoes an order-2 reflection while the upper arm does not, and gravity acts in the opposite sense for the order-1 reflection. This asymmetry can be removed if the $|0\rangle \to (|0\rangle + |2\hbar k\rangle)/\sqrt{2}$ beam-splitting operation is available. This requires a traveling standing wave, rather than the static standing wave used up to now [14]. An interferometer could be implemented by following this beam splitter with order-2 reflections at intervals of $t_2 = 2\hbar k/mg$. Each packet would undergo the same operations during a cycle so the reflection phases would largely cancel. In addition, the average packet separation is twice as large, leading to a proportionally greater sensitivity to g. We have implemented an interferometer of this sort, but the beam splitter was not sufficiently consistent to achieve clear results. We plan to implement a more reliable splitter using, for instance, the method of Ref. [11].

A traveling standing wave also permits more complex interferometer schemes, such as that of Fig. 1(d). This trajectory starts with the beam splitter described above. A time t_2 later, an order-2 reflection is applied, making $p = 0$ for the upper packet and $p = +2\hbar k$ for the lower packet. This is immediately followed by a π pulse on the transition $|0\rangle \leftrightarrow |+2\hbar k\rangle$, leaving the upper trajectory moving upward and the lower trajectory stationary. Another time t_2 later, the same operations can be repeated, resulting in an increasing vertical separation of the packets as shown. When desired, the operations are reversed, bringing the packets back together and closing the interferometer in a symmetric way. Here the spacing between the packets grows with the total measurement time just as in an interferometer with free-falling atoms. The fundamental sensitivity would therefore be comparable to that obtained with falling atoms, but the minimal vertical space required would be a substantial advantage.

The gravimetry techniques discussed here can be directly compared to measurements using Bloch oscillations in an optical lattice, in which the same type of reflections occur but in a lattice that is continuously present [10]. As a result, the momentum state of the atoms oscillates at the Bloch frequency $\Omega = (\pi g)/v_r$. By measuring Ω, a value for g can be obtained. If the measurement occurs over time T and is shot-noise limited, then the uncertainty $\delta\Omega$ will be $1/(T\sqrt{\mathcal{N}})$ for atom number $\mathcal{N}$. This gives an uncertainty $\delta g = (v_r/\pi)(T\sqrt{\mathcal{N}})^{-1}$. To compare, in our scheme the interferometer phase can be measured to an accuracy of $1/\sqrt{\mathcal{N}}$ for an uncertainty $\delta g = (\partial g/\partial\Phi)/\sqrt{\mathcal{N}}$. From (5),

$$\frac{\partial\Phi}{\partial g} = 2Nk\tau^2 = Tk\tau = \frac{Tkv_r}{g}.$$

This gives $\delta g = (g/v_r k)(T\sqrt{\mathcal{N}})^{-1}$, better than the Bloch method by a factor of 9 for the case of ^{87}Rb.

In conclusion, we have demonstrated the ability to suspend otherwise unconfined atoms in gravity for over 100 ms, using repeated reflections from a standing-wave laser beam. We note that free atoms would fall a distance of 5 cm in this time. To achieve this, we developed high-precision reflection operations, for which our model predicts that a factor of 10 greater suspension time should be possible. We further demonstrated a gravitationally sensitive atom interferometer using the suspended atoms. With some improvements, this technique might be able to achieve gravimetric precision similar to that of free-falling atom interferometers, but with a much reduced space requirement.

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