Long Atomic Coherence Times in an Optical Dipole Trap

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Sodium atoms have been stored in a blue-detuned dipole trap based on sheets of argon ion laser light which support against gravity. In this trap, the atoms spend most of their time in free fall, resulting in a large reduction in the perturbation of the atomic levels due to the trapping potential. This reduction enabled us to probe the ground state hyperfine splitting with a measurement time of 4 s, yielding a linewidth of 0.125 Hz and a Ramsey fringe contrast of 43%. The coherence time was ~300 times longer than achieved in a red-detuned Nd:YAG laser dipole trap with comparable depth.

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The ability to laser cool neutral atoms has permitted a dramatic increase in the time one can measure an atomic transition in a perturbation free environment. For example, the microwave measurement of the 9.2 GHz ground state hyperfine transition in a cesium atomic fountain has allowed a measurement time of $\sim 1/3$ s, corresponding to FWHM linewidth of ~1.5 Hz [1]. Geometrical considerations limit the height of the atomic fountain, and measurement times significantly longer than 1 s are not practical.

Atoms have been confined in optical, magnetic [2], and magneto-optic traps [3] for as long as several hours, but all of these traps are based on the perturbation of the atomic energy levels by externally applied fields. The traps introduce large inhomogeneous energy shifts of ground state hyperfine levels that severely limit the precision of spectroscopic measurement. In order to minimize this perturbation, one can attempt to design a trap where the atoms are confined by hard walls and spend most of their time at zero potential. For example, in a trap based on a sheet of blue-detuned light supporting against gravity, the ac Stark shifts are 10^4–10^5 times smaller than for a comparably deep red-detuned trap, where the atoms predominantly experience the maximum light intensity. In addition, if the detuning δ of the trapping light is much larger than the hyperfine frequency difference between ground state levels $\delta_{\rm hf}$, and the beam is linearly polarized, then the relative Stark shift is suppressed by a factor of $\delta/\delta_{\rm hf}$. A large detuning also improves the coherence time of atoms in the trap as the photon scattering rate is inversely proportional to δ^2. Finally, if the atoms are confined to a dimension less than the wavelength of the transition (Lamb-Dicke regime), then Doppler broadening becomes negligible. The combination of these factors allows high precision rf spectroscopy of atoms in far-blue-detuned light trap.

A hard wall with a characteristic length of $\lambda/2\pi$ may be constructed using a blue-detuned evanescent light field [4]. Bouncing of cold atoms from evanescent light waves has been observed by a number of groups [5,6]. However, previously demonstrated atomic trampolines could not be used for precision spectroscopic measurements for two reasons: The longest $1/e$ storage times were on the order of 100 ms [5], and the detuning of the trapping light was relatively small (typically $\sim 10^9$ Hz), resulting in a high photon scattering rate. Both these limitations arose due to the fact that the atoms were dropped from a height of a few mm, necessitating a strong dipole potential to support them (the minimum drop height is constrained by the problem of placing a glass surface close to the source of cold atoms). For example, cesium atoms dropped from a height of 3 mm gain a kinetic energy of $\sim 6000 U_{\rm rec}$, where $U_{\rm rec} = (\hbar k)^2/2M$ is the photon recoil energy. The intensity required to produce the necessary dipole force and simultaneously avoid a high photon scattering rate has prompted a number of groups to study ways of enhancing the light intensity by dielectric coatings [7] or surface plasmon resonances [8].

We have attempted to sidestep these difficulties by constructing a blue-detuned dipole trap based on free-propagating laser beams. This trap can be placed at the center of the source of cold atoms such that the atoms do not gain significant kinetic energy during loading. The trap was constructed from linearly polarized laser beams copropagating along the y axis. The beams were focused to form two elliptical sheets of light (15 μm × 1100 μm, $1/e^2$ diameters) and overlapped with the major axes of the ellipses at ±45° to the vertical in order to form a "V" cross section. Figure 1 shows the calculated potential seen by an atom confined in a horizontal plane 30 μm above the intersection of the two beams. Confinement along the laser propagation direction y is provided by the divergence of the focused light sheets.

The two cylindrical beams were produced by the 488 and 514.5 nm lines of an argon laser. This geometry avoids intensity and polarization gradients at the intersection. With 15 W (all lines) from an argon laser, the power of 488 and 514.5 nm lines was 4 and 6 W, respectively, corresponding to a maximum dipole potential of $90 U_{\rm rec}$ and $190 U_{\rm rec}$. The large detuning of the argon light from the Na 589 nm D lines ($\sim 10^{14}$ Hz) means that the relative Stark shift between the $F = 1$, $m_F = 0$ and $F = 2$, $m_F = 0$ ground states was only $\delta_{\rm hf}/\delta \approx 2.2 \times 10^{-5}$ of

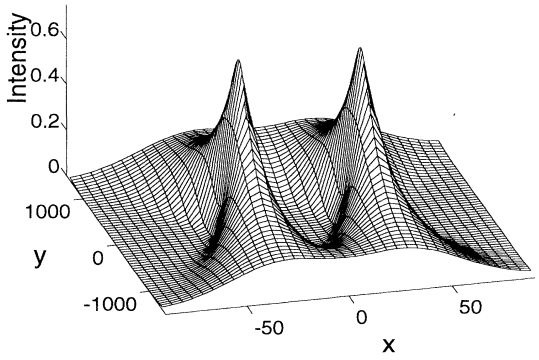

FIG. 1. The light intensity experienced by an atom confined in plane 30 μm above the intersection of two focused sheets of light. The x, y dimensions are in microns. The intensity is normalized to the peak laser intensity.

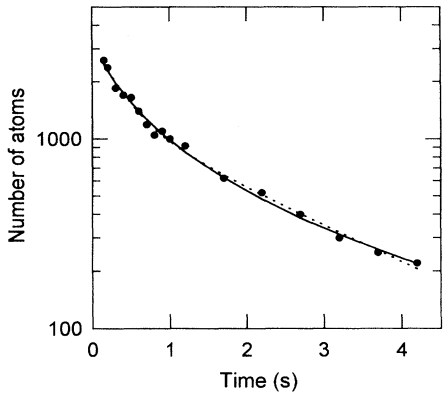

FIG. 2. Number of atoms N in the trap as a function of time. The circles are experimental data. The full line is a fit based on a solution to the equation $dN/dt = -N/\tau - \beta N^2$, and yields $\tau = 4.8$ s and $\beta = 0.000\,58$ s^{-1}. The dashed line is a fit by the sum of two exponentials $N(t) = -N_1 \exp(-t/\tau_1) - N_2 \exp(-t/\tau_2)$, and yields $\tau_1 = 2.2$ s and $\tau_2 = 0.35$ s.

the Stark shift for each state. The average rate for spontaneously scattering photons at such detunings was calculated to be 10^{-3}–10^{-4} s^{-1}.

The trap was loaded by overlapping the argon beams with a magneto-optic trap (MOT) [9]. The MOT itself was loaded from a beam of thermal Na atoms that was slowed by a counterpropagating, frequency chirped laser beam. A detailed description of our apparatus can be found elsewhere [10]. The argon beams were on throughout the MOT formation time. After 465 ms, the magnetic field, atomic beam, slowing beam, and MOT beams were shut off, leaving only the dipole trap beams present. The intensity of the MOT beams that maximized the number of atoms loaded into the dipole trap was ~2.5 mW/cm^2. By reducing the intensity of the $3S_{1/2}$, $F = 1 \rightarrow 3P_{3/2}$, $F = 2$ repumping sideband of the MOT beams from ~25% to ~5% (of that of the $F = 2 \rightarrow F = 3$ carrier frequency) for the last 10 ms of the MOT, the number of atoms loaded increased by a factor of 3, giving ~3000 atoms. By partially optically pumping the atoms into the $F = 1$ ground hyperfine state, we suppress known exothermic mechanisms such as ground state hyperfine changing collisions, photoassociative collisions, and also reduce radiative repulsive forces [11]. Finally, the atoms were optically pumped into the $3S_{1/2}$, $F = 1$ state by shutting off the repumping sideband for the last 0.5 ms.

The number of atoms in the trap as a function of time after the end of the loading process shown in Fig. 2 was measured by turning on the MOT beams well above the saturation intensity and imaging the fluorescence with a calibrated photomultiplier tube. The slow exponential time constant of $\tau = 4.8$ s is consistent with losses due to collisions with background gas atoms (the background pressure was 2×10^{-10} Torr) [12]. The initial fast loss rate may result from atoms in unstable orbits which eventually spill over the edge of the trap. A high sensitivity of the short decay time to the relative alignment between the two cylindrical beams supports this conclusion.

We performed rf spectroscopy on the trapped atoms by driving the magnetic-field insensitive transition between the $F = 1$, $m_F = 0$ and $F = 2$, $m_F = 0$ ground state levels. The transition was excited with a ~177 GHz rf traveling wave, emitted from a 11.4 cm square open-ended aluminum tube that was located outside the vacuum chamber, ~30 cm from the atoms. The microwave frequency was locked to a Loran C timing signal. A bias magnetic field of ~5 mG was applied to separate the magnetic-field sensitive transitions from the $m_F = 0 \rightarrow m_F = 0$ transition. The number of atoms making the transition to the $F = 2$ state was determined by measuring the fluorescence from a short pulse of light resonant with the $3S_{1/2}$, $F = 2 \rightarrow 3P_{3/2}$, $F = 3$ transition.

The rf transition was excited using Ramsey's method of separated oscillatory fields [13] by applying two $\pi/2$ pulses, separated by a measurement time T. The Rabi frequency during the pulses was 25 kHz, and the bias magnetic field was parallel to the polarization axis of the rf field. The resulting central Ramsey fringes for $T = 4$ s are shown in Fig. 3, together with a fit of the form $a + b\cos(2\pi f T + \phi)$. A constant background, due mainly to scattered light, was measured with the rf power off and subtracted from the signal to determine the baseline of Fig. 3. The signal to noise ratio improved at the higher laser intensities, as more atoms were trapped. With 200 data points (900 s of data collection) the line center had a fitted uncertainty of ∓ 1.3 mHz. The fit yields a fringe contrast $b/a = 43\%$. The fringe contrast after $T = 0.2$, 1, and 2 s were 98%, 90%, and 82%, respectively. These values were fitted by the function $\exp[-(T/T_c)^2]$ which gives a $1/e$ coherence decay time $T_c = 4.4$ s. The short-term frequency stability was $40/\sqrt{t}$ [mHz/$\sqrt{\text{s}}$] with

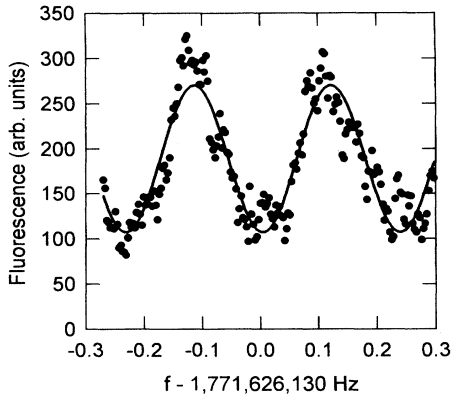

FIG. 3. The central Ramsey fringes of the $F = 1$, $m_F = 0$ to $F = 2$, $m_F = 0$ transition with a 4 s measurement time. The circles are the measured data, and the line is a fit by $a + b\cos(2\pi fT + \phi)$. A constant background, present without rf pulses, was subtracted from the data.

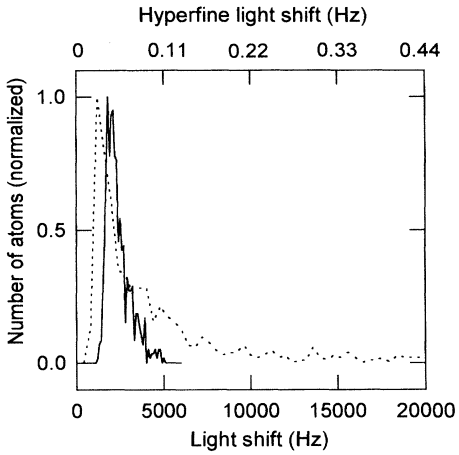

FIG. 4. Stark shift distributions for atoms stored in blue-detuned dipole traps calculated by a Monte Carlo simulation. The dotted line corresponds to the two-beam trap used in the experiment. The solid line is for the proposed three-beam trap discussed in the text.

20 W argon laser power. Over a few hours, frequency drifts of several tens of mHz were observed due to the quadratic Zeeman shift αB^2, where α is $\sim$2.2 mHz/mG^2 for Na.

The Stark shift of the hyperfine transition was determined by measuring the frequency of the central Ramsey fringe at $T = 1$ s as a function of the trapping laser power P (the 488 and 514.5 nm lines are $\sim 0.25P$ and $\sim 0.4P$, respectively). We measure a frequency shift linearly proportional to P with a slope of $\sim$18 mHz/W. The Stark shift at $P = 15$ W was 270 mHz. Since most of the trap parameters such as the density, bounce frequencies, and velocities of the atoms depend on the trapping laser intensity, a simple proportionality is not necessarily expected.

The dominant source of dephasing between the Ramsey pulses is the broad distribution of Stark shifts experienced by different atoms. We calculated these shifts and the coherence time for the atoms in the trap using a Monte Carlo simulation [14]. The distribution of average Stark shifts for atoms that remained in the trap after 1 s is shown in Fig. 4 (dotted line). The hyperfine Stark shift distribution (upper scale) is obtained by dividing the frequency scale by $\delta/\delta_{\rm hf} \approx 4.5 \times 10^4$. The distribution yields a coherence decay time $T_c = 9$ s and a frequency shift of the central Ramsey fringe of 70 mHz [15]. The discrepancy between the calculated and experimental values may be attributed to aberrations in the trapping laser beams.

The asymmetric geometry of our present trap permits wildly different trajectories and hence a broad distribution of integrated Stark shifts. A longer coherence time would be observed in a more symmetric trap where there is a strong temporal averaging of the integrated Stark shift. As an example, the solid line in Fig. 4 shows the Stark shift distribution calculated for atoms trapped in an inverted pyramid, formed by three sheets of light, propagating at 45° to gravity and 90° to each other [16]. The calculated Stark shift distribution gave a coherence decay time $T_c = 35$ s, a factor of $\sim$4 increase compared to the two-beam trap. The average Stark shift decreased by $\sim$35%, to 45 mHz. In this trap, the net effect of many collisions with the walls is to induce an average phase shift which is approximately the same for all atoms. Similar averaging is seen with atoms confined at higher temperatures. For example, hydrogen atoms trapped in a Teflon coated glass bulb of a hydrogen maser [17] and atoms confined in a cell with buffer gases [18] can undergo a large number of collisions before the relevant atomic coherence is destroyed.

We also performed rf spectroscopy of Na atoms in a far-off resonance, red-detuned dipole trap that was realized by focusing a 10 W Nd:YAG laser beam ($\lambda = 1.06$ μm) to a 75 μm $1/e^2$ diameter spot. The depth of the dipole potential ($\sim 150U_{\rm rec}$) was comparable to that of our blue-detuned trap, and the detuning from the Na D lines (2.26×10^{14} Hz) was $\sim$2.5 times larger. Still, we measured a coherence time of only $T_c \approx 15$ msec, a factor of $\sim$300 smaller than for the blue-detuned trap. This result clearly illustrates the advantage of the blue-detuned geometry.

To reproduce the 4 s Ramsey fringes reported above would require a 20 m atomic fountain. However, despite this advance it is not obvious that a far-off resonance blue-detuned dipole trap can supersede a fountain as an atomic clock because of the residual ac Stark shifts. On the other hand, this type of trap may be useful for measuring a permanent electric dipole moment in atoms [19]. It combines many of the better features of atomic beam measurements [20] and cell experiments [18] in that high electric fields could be used while systematic effects

such as magnetic-field inhomogeneities over the sample volume, $\mathbf{v} \times \mathbf{E}$ shifts, and leakage currents due to cell walls would be suppressed. We are hopeful that over 10^6 atoms can be trapped with coherence times of over 30 s. In addition, blue-detuned dipole traps offer great promise for achieving high atomic phase-space densities as a "flat bottomed" potential helps to avoid runaway three-body recombination [21].

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[14] In the simulations, the classical equations of motion were integrated for 10^4 atoms with initial Gaussian distributions in position and velocities (the rms position and velocity were 500 μm and 25 cm/sec, respectively). ~500 atoms remain in the $P = 15$ W trap after 1 s. Changing the initial rms values by $\times 2$ and $\times 0.5$ changed the distribution of the Stark shifts by less then 10% (although the number of remaining atoms changes significantly).

[15] The fringe contrast is calculated by $\int \cos[\pi T(f - \delta f)]N(f)\,df / \int N(f)\,df$, where $N(f)$ is the light shift distribution of Fig. 4, and δf is the frequency shift of the Ramsey fringe that is found by maximizing the contrast.

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