Ultrastable CO_2 Laser Trapping of Lithium Fermions

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We demonstrate an ultrastable CO_2 laser trap that provides tight confinement of neutral atoms with negligible optical scattering and minimal laser-noise-induced heating. Using this method, fermionic ^{6}Li atoms are stored in a 0.4 mK deep well with a $1/e$ trap lifetime of 300 sec, consistent with a background pressure of 10^{-11} Torr. To our knowledge, this is the longest storage time ever achieved with an all-optical trap, comparable to the best reported magnetic traps. [S0031-9007(99)09193-0]

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Off-resonance optical traps have been explored for many years as an attractive means of tightly confining neutral atoms [1]. Far off resonance optical traps (FORTs) employ large detunings from resonance to achieve low optical heating rates and high density, as well as to enable trapping of multiple atomic spin states in nearly identical potentials [2–6]. For CO_2 laser traps [7], the extremely large detuning from resonance and the very low optical frequency lead to optical scattering rates that are measured in photons per atom per *hour*. Hence, optical heating is negligible. Such traps are potentially important for the development of new standards and sensors based on spectroscopic methods, for precision measurements such as determination of electric dipole moments in atoms [8], and for fundamental studies of cold, weakly interacting atomic or molecular vapors.

However, all-optical atom traps have suffered from unexplained heating mechanisms which limit the minimum attainable temperatures and the maximum storage times in an ultrahigh vacuum [4,9,10]. Recently, we have shown that to achieve long storage times in all-optical traps that are not limited by optical heating rates, heating arising from laser intensity noise and beam pointing noise must be stringently controlled [11,12]. Properly designed CO_2 lasers are powerful and extremely stable in both frequency and intensity [13,14], resulting in laser-noise-induced heating times that are measured in hours. Hence, in an ultrahigh vacuum (UHV) environment, where loss and heating arising from background gas collisions are minimized [15,16], extremely long storage times should be obtainable using ultrastable CO_2 laser traps.

In this Letter, we report storage of ^{6}Li fermions in an ultrastable CO_2 laser trap. Trap $1/e$ lifetimes of 300 sec are obtained, consistent with a background pressure of 10^{-11} Torr. This constitutes the first experimental proof of principle that extremely long storage times can be achieved in all-optical traps. Since arbitrary hyperfine states can be trapped, this system will enable exploration of s-wave scattering in a weakly interacting Fermi gas.

The well depth for a focused CO_2 laser trap is determined by the induced dipole potential $U = -\alpha_g \bar{\mathcal{E}}^2/2$, where α_g is, to a good approximation, the ground state *static* polarizability [7], and $\bar{\mathcal{E}}^2$ is the time average of the square of the laser field. In terms of the maximum laser intensity I for the Gaussian CO_2 laser beam, the ground state well depth U_0 in Hz is

$$\frac{U_0}{h}\,(\mathrm{Hz}) = -\frac{2\pi}{hc}\,\alpha_g I\,. \tag{1}$$

In our experiments, a laser power of $P = 40$ W typically is obtained in the trap region. A lens is used to focus the trap beam to a field $1/e$ radius of $a_f = 50$ μm, yielding an intensity of $I = 2P/(\pi a_f^2) \simeq 1.0$ MW /cm^2. For the I-P(20) line with $\lambda_{CO_2} \simeq 10.6$ μm, the Rayleigh length is $z_0 = \pi a_f^2/\lambda_{CO_2} = 0.74$ mm. Using the Li ground state polarizability of $\alpha_g = 24.3 \times 10^{-24}$ cm^3 [17] yields a well depth of $U_0/h = -8$ MHz, which is approximately 0.4 mK. For this tight trap, the ^{6}Li radial oscillation frequency is 4.7 kHz and the axial frequency is 0.22 kHz.

For ^{6}Li in a CO_2 laser trap, both the excited and the ground states are attracted to the well. The excited state static polarizability is $\alpha_p = 18.9 \times 10^{-24}$ cm^3 [17], only 20% less than that of the ground state. With a ground state well depth of 8 MHz, the frequency of the first resonance transition in the trap is shifted by only 1.6 MHz at the center of the trap and thus does not significantly alter the operation of the magneto-optical trap (MOT) from which the trap is loaded.

The optical scattering rate R_s in the CO_2 laser trap arises from Larmor scattering [7] and can be written as $R_s = \sigma_S I/(\hbar c k)$, where the Larmor scattering cross section σ_S is

$$\sigma_S = \frac{8\pi}{3}\,\alpha_g^2 k^4. \tag{2}$$

Here, $k = 2\pi/\lambda_{CO_2}$. Using $\alpha_g = 24.3 \times 10^{-24}$ cm^3 yields $\sigma_S = 5.9 \times 10^{-30}$ cm^2. At 1.0 MW /cm^2, the scattering rate for lithium is then 2.9×10^{-4} sec^{-1}, corresponding to a scattering time of $\simeq$3400 sec for one photon per atom. As a result, the recoil heating rate is negligible.

Heating can arise from laser intensity noise and beam pointing fluctuations [11,12]. For simplicity, we estimate the noise-induced heating rates for our trap using a harmonic oscillator approximation which is valid for atoms

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near the bottom of the well. This provides only a rough estimate of the expected heating rates in the Gaussian well, since the trap oscillation frequency decreases as the energy approaches the top of the well. A detailed discussion of noise-induced heating in Gaussian potential wells will be given in a future publication. In the harmonic oscillator approximation, intensity noise causes parametric heating and an exponential increase in the average energy for each direction of oscillation, $\langle \dot{E} \rangle = \Gamma \langle E \rangle$, where the rate constant in $\sec^{-1}$ is

$$\Gamma = \pi^2 \nu^2 S_I(2\nu). \quad (3)$$

Here ν is a trap oscillation frequency and $S_I(2\nu)$ is the power spectrum of the fractional intensity noise in fraction^2/Hz. For our CO_2 laser, $S_I(9.4\ \text{kHz}) \leq 1.0 \times 10^{-13}/\text{Hz}^{-1}$, where it is comparable to the detector noise. This is 3 orders of magnitude lower than that measured for an argon ion laser [11]. The corresponding heating time for radial oscillation in our trap at $\nu = 4.7$ kHz is $\Gamma^{-1} \geq 4.6 \times 10^4$ sec. For the axial oscillation, $\nu = 220$ Hz, $S_I(440\ \text{Hz}) \simeq 1.1 \times 10^{-11}\ \text{Hz}^{-1}$ and $\Gamma^{-1} \simeq 2 \times 10^5$ sec.

Fluctuations in the position of the trapping laser beam cause a constant heating rate $\langle \dot{E} \rangle = \dot{Q}$, where

$$\dot{Q} = 4\pi^4 M \nu^4 S_x(\nu). \quad (4)$$

Here M is the atom mass and S_x is the position noise power spectrum in cm^2/Hz at the trap focus. For ^{6}Li, one obtains $\dot{Q}(\text{nK/s}) = 2.8 \times 10^{-4} \nu^4(\text{Hz}) S_x(\mu\text{m}^2/\text{Hz})$. Position noise only couples directly to the radial motion where $\nu \simeq 4.7$ kHz. For our laser, $S_x(4.7\ \text{kHz}) \leq 3.4 \times 10^{-10}\ \mu\text{m}^2/\text{Hz}$, where the upper bound is determined by the noise floor for our detection method. This yields $\dot{Q} \leq 46$ nK/s. Hence, we expect the trap lifetime to be limited by the background pressure of our UHV system.

The expected number of trapped atoms N_T can be estimated as follows. We take the trapping potential to be approximately Gaussian in three dimensions:

$$U(\vec{x}) = -U_0 \exp(-x^2/a^2 - y^2/b^2 - z^2/z_0^2), \quad (5)$$

where $a = b = a_f/\sqrt{2}$ is the intensity $1/e$ radius and z_0 is the Rayleigh length. Here, the Lorentzian dependence of the trap beam intensity on the axial position z is approximated by a Gaussian dependence on z.

We assume that, after a sufficient loading time, atoms in the CO_2 laser trap will come into thermal and diffusive equilibrium with the MOT atoms that serve as a reservoir [18]. The density of states in the Gaussian trap and the occupation number then determine the number of trapped atoms, which takes the form

$$N_T = n V_{\text{FORT}} F[U_0/(k_B T)]. \quad (6)$$

Here the volume of the CO_2 laser trap is defined as $V_{\text{FORT}} = a^2 z_0 \pi^{3/2}$. Hence, nV_{FORT} is the total number of atoms contained in the volume of the FORT at the MOT density n.

$F(q)$ determines the number of trapped atoms compared to the total number contained in the FORT volume at the MOT density. It is a function only of the ratio of the well depth to the MOT temperature, $q \equiv U_0/(k_B T)$:

$$F(q) = \frac{q^{3/2}}{2} \int_0^1 dx\, x^2 g(x) \exp[q(1-x)]. \quad (7)$$

Here $g(x)$ is the ratio of the density of states for a Gaussian well to that of a three-dimensional harmonic well:

$$g(x) = \frac{\beta^{3/2}(1-x)^{1/2}}{x^2} \frac{16}{\pi} \times \int_0^1 du\, u^2 \sqrt{\exp[\beta(1-u^2)] - 1}, \quad (8)$$

where $\beta \equiv -\ln(1-x)$. The variable $x = (E + U_0)/U_0$ is the energy of the atom relative to the bottom of the well in units of the well depth, where $-U_0 \leq E \leq 0$, and $g(0) = 1$. For our MOT, the typical temperature is 1 mK, $n \simeq 10^{11}$ cm^3, and $nV_{\text{FORT}} = 5 \times 10^5$ atoms. Using the well depth of $U_0 = 0.4$ mK in Eq. (6) shows that N_T is of the order of 6×10^4 atoms. Much higher numbers are obtainable for a deeper well at lower temperature.

The experiments employ a custom-built, stable CO_2 laser. High-voltage power supplies, rated at 10^{-6} fractional stability at full voltage, proper electrode design, and negligible plasma noise enable highly stable current. Heavy mechanical construction, along with thermally and acoustically shielded invar rods, reduces vibration. The laser produces 56 W in an excellent TEM_{00} mode.

The CO_2 laser beam is expanded using a ZnSe telescope. It is focused through a double-sealed, differentially pumped, 5 cm diameter ZnSe window into a UHV system. The vacuum is maintained at $\simeq 10^{-11}$ Torr by a titanium sublimation pump. The trap is at the focus of a 19 cm focal length ZnSe lens.

The trap is continuously loaded from a ^{6}Li MOT employing a standard $\sigma_\pm$ configuration [19] with three orthogonal pairs of counterpropagating, oppositely polarized 671 nm laser beams, each 2.5 cm in diameter and 8 mW. Power is supplied by a Coherent 699 dye laser that generates 700 mW. The MOT magnetic field gradient is 15 G/cm (7.5 G/cm) along the radial (axial) directions of the trap. The MOT is loaded from a multicoil Zeeman slower system [20] that employs a differentially pumped recirculating oven source [21]. Using a calibrated photomultiplier, the MOT is estimated to trap approximately 10^8 ^{6}Li atoms. The MOT volume is found to be $\simeq 1$ mm^3. This yields a density of 10^{11} cm^3, consistent with that obtained for lithium in other experiments [22,23]. Using time-of-flight methods, we find typical MOT temperatures of 1 mK.

We initially align the CO_2 laser trap with the MOT by using split-image detection of the fluorescence at 671 nm to position the focusing ZnSe lens in the axial direction.

The focal point for the trapping beam is positioned in the center of the MOT, taking into account the difference in the index of refraction of the optics at 671 nm and 10.6 μm. A 671 nm laser beam is aligned on top of the CO_2 laser beam to align the transverse position of the focal point in the MOT. Since the Rayleigh length is short and the focus is tight, this method does not reliably locate the actual focus of the CO_2 beam. Hence, a spectroscopic diagnostic based on the light shift induced by the CO_2 laser is employed for the final alignment of the trapping beam.

While the near equality of the Li excited and ground state polarizabilities is ideal for continuous loading from the MOT, it makes locating the CO_2 laser focus in the MOT by light shift methods quite difficult. To circumvent this problem, a dye laser at 610 nm is used to excite the $2p$-$3d$ transition for diagnostics. At the 10.6 μm CO_2 laser wavelength, we estimate that the $3d$ state has a scalar polarizability of approximately 700×10^{-24} cm^3 [24], nearly 30 times that of the $2s$ or $2p$ state. In the focus of the CO_2 laser, the corresponding light shift is $\simeq -300$ MHz. Chopping the CO_2 laser beam at 2 kHz and using lock-in detection of fluorescence at 610 nm yields a two-peaked light shift spectrum. This two-peaked structure arises because the lock-in yields the difference between signals with the CO_2 laser blocked and unblocked. At the ideal focusing lens position, the amplitude and the frequency separation of these peaks are maximized. Optical alignment remains unchanged for months after this procedure.

Measurement of the trapped atom number versus time is accomplished by monitoring the fluorescence at 671 nm induced by a pulsed, retroreflected probe/repumper beam (1 mW, 2-mm diameter). The probe is double blinded by acousto-optic (A/O) modulators to minimize trap loss arising from probe light leakage. The loading sequence is as follows: The CO_2 laser trap is continuously loaded from the MOT for 10 sec. This provides adequate time for the MOT to load from the Zeeman slower. Then the MOT repumping beam is turned off, so that atoms in the upper $F = 3/2$ hyperfine state are optically pumped into the lower $F = 1/2, M = \pm 1/2$ states. After 25 μsec, the optical MOT beams are turned off using A/O modulators, and a mechanical shutter in front of the dye laser is closed within 1 ms to eliminate all MOT light at 671 nm. The MOT gradient magnets are turned off within 0.2 ms. After a predetermined time interval between 0 and 600 sec, the probe beam is pulsed to yield a fluorescence signal proportional to the number of trapped atoms. The detection system is calibrated and the solid angle is estimated to determine the atom number. Typical trapped atom numbers measured in our initial experiments are $\simeq 2.3 \times 10^4$. This corresponds to the predictions of Eq. (6) for a well depth of 0.25 mK. Since we expect the potential of the MOT gradient magnet to lower the effective well depth from 0.4 mK by $\simeq$0.15 mK during loading, the measured trap number is consistent with our predictions.

Figure 1 shows the decay of the trapped atom number on a time scale of 0–600 sec. Each data point is the mean obtained from four separate measurement sequences through the complete decay curve. The error bars are the standard deviation from the mean. Atoms in the $F = 1/2$ state exhibit a single exponential decay with a time constant of 297 sec, clearly demonstrating the potential of this system for measurements on a long time scale.

We have observed that an initial (10–15)% decrease in the signal can occur during the first second. This may arise from inelastic collisions between atoms in the $F = 1/2$ state with atoms that are not optically pumped out of the upper $F = 3/2$ state. During optical pumping, fluorescence from the $F = 3/2$ state decays in $\simeq 5$ μsec to a $\simeq$5% level which persists for a few milliseconds, consistent with a residual $F = 3/2$ population.

The lifetime of atoms in the $F = 1/2$ state can be limited by processes that cause heating or direct loss. If we attribute the trap lifetime entirely to residual heating, the heating rate from all sources would be, at most, 400 μK/300 sec $\simeq$ 1 μK/sec, which is quite small. However, if the loss were due to heating, one would expect a multimodal decay curve, analogous to that predicted in Ref. [12]. Instead, we observe a single exponential decay as expected for direct loss mechanisms, such as collisions with background gas atoms or optical pumping by background light at 671 nm (into the unstable $F = 3/2$ state). If we assume that the lifetime is background gas limited and that Li is the dominant constituent, the measured lifetime of 297 sec is consistent with a pressure of $\simeq 10^{-11}$ Torr.

The long lifetime of the $F = 1/2$ state is expected, based on the prediction of a negligible s-wave elastic

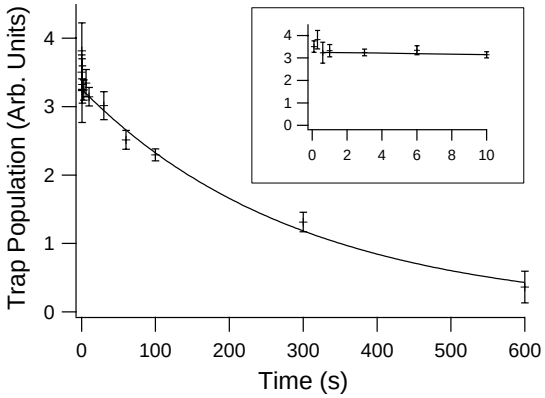

FIG. 1. Trapped number of atoms versus time for an ultrastable CO_2 laser trap. The solid line is a single exponential fit, $N(t) = A\exp(-t/\tau)$, and gives $\tau = 297$ sec. We believe that a small fraction of atoms are lost at short times $\leq$1 sec (see inset, 0–10 sec) from collisions with atoms that remain in the $F = 3/2$ state after optical pumping. Hence, the first two points at 0.1 and 0.3 sec are neglected in the fit. The trap lifetime for the remaining $F = 1/2$ atoms is 297 sec, to our knowledge the longest ever obtained with an all-optical trap.

scattering length ($\ll$1 bohr) at zero magnetic field [25]. Hence, spontaneous evaporation should not occur. We have made a preliminary measurement of trap loss arising from inelastic collisions when the $F = 3/2$ state is occupied. This is accomplished by omitting the optical pumping step in the loading sequence described above. The trap is found to decay with a $1/e$ time <1 sec when 2.3×10^4 atoms are loaded (density $\simeq 10^9$ cm^{-3}). A detailed study of elastic and inelastic collisions at low magnetic field is in progress.

In conclusion, we have demonstrated a 300 sec $1/e$ lifetime for lithium fermions in an ultrastable CO_2 laser trap with a well depth of 0.4 mK. By using an improved aspherical lens system, an increase in trap depth to 1 mK is achievable. Furthermore, Eq. (6) shows that, if the MOT temperature is reduced to 0.25 mK, more than 10^6 atoms can be trapped in a 1 mK deep well. Since the ground and excited state trapping potentials are nearly identical, exploration of optical cooling schemes may be particularly fruitful in this system. Currently, we are exploring ^{6}Li as a fundamental example of a cold, weakly interacting Fermi gas. By trapping multiple hyperfine states, it will be possible to study both elastic and inelastic collisions between fermions. The combination of long storage times and tight confinement obtainable with the CO_2 laser trap, as well as the anomalously large scattering lengths for ^{6}Li [26,27], makes this system an excellent candidate for evaporative cooling and potential observation of a Bardeen-Cooper-Schrieffer transition. Furthermore, this system is well suited for exploring novel wave optics of atoms and molecules, such as coherent changes of statistics by transitions between free fermionic atoms and bosonic molecules, analogous to free-to-bound transitions for bosonic atoms [28].

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