RAPID COMMUNICATIONS

PHYSICAL REVIEW A VOLUME 47, NUMBER 6 JUNE 1993

Far-off-resonance optical trapping of atoms

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(Received 2 December 1992)

We confine ^{85}Rb atoms in an optical dipole force trap with a very large detuning from resonance of up to 65 nm. Confinement times of 200 ms, limited only by background-gas collisions, are obtained without additional cooling. A typical trap contains 1300 atoms at a temperature of 0.4 mK and a peak density of 8×10^{11} cm^{-3}. We measure spontaneous photon scatter rates of the trapped atoms to be less than 1.6×10^{3} s^{-1}, corresponding to recoil heating rates below 0.6 mK/s. The far-detuned trap confines atoms with a strong, nearly conservative optical force and negligible atomic excitation.

PACS number(s): 32.80.Pj

The need for dense samples of cold atoms for applications such as precision spectroscopy or studies of cold atomic collisions or collective effects has motivated the development of optical [1–4] and magnetic [5] traps for neutral atoms. Optical traps have the advantage of a restoring force that is typically larger than that of a magnetic trap. They can also trap an atom in any spin state. Unfortunately, in the optical traps demonstrated thus far an appreciable fraction of the atoms are excited, and the spontaneous photon scatter rates are quite large. This limits the achievable density in optical traps, due to excited-state trap-loss collisions [6] and to repulsive rescattering forces between the atoms [7]. Also, the large spontaneous photon scatter rates rapidly destroy ground-state atomic polarization or coherence and further limit the application of optical atom traps.

In this paper, we report the trapping of ^{85}Rb atoms in an optical-dipole-force atom trap that operates at very large detunings—up to 65 nm—from atomic resonance. The atoms in this far-off-resonance trap (FORT) [8] have a very low spontaneous scatter rate and negligible photon recoil heating. Long confinement times are achieved with *no additional cooling*. In this regime, the potential closely approximates the ideal of a truly *conservative* trapping potential. While the restoring force of our trap is still quite strong, the excited-state collision rates, rescattering forces, and ground-state relaxation rates are dramatically reduced [8] relative to previous optical traps.

The optical dipole force on a two-level atom of resonance frequency ω_0 in a laser field of frequency ω_L can be derived from a potential $U=\hbar\Omega^2/4\Delta$ [9,10]. Here, Ω is the Rabi frequency, $\Delta=\omega_L-\omega_0$ is the laser detuning, and we assume $\Delta\gg\Omega,\Gamma$, with Γ the spontaneous-emission rate of the atom. Atoms spontaneously scatter photons from the field at a rate $\gamma_s=\Gamma\Omega^2/4\Delta^2$. (We calculate the numbers presented below with slightly modified expressions that apply to the multilevel ^{85}Rb atoms.) The simplest optical dipole trap consists of a single, focused, Gaussian laser beam tuned below resonance [1]. The advantage of a large detuning can be seen from the formulas for U and γ_s. If Ω^2 (proportional to laser intensity) can be increased as Δ is increased then the same potential well depth can be obtained with a reduced scatter rate. For every scattered photon an atom is heated by twice the recoil energy $R=(\hbar k)^2/2m$ where m is the atomic mass and $k=\omega_L/c$ [9]. Photon recoil heating limits the lifetime of atoms in the trap to $\tau_h=U_0/2R\gamma_s$ where U_0 is the potential well depth [9]. (For the detunings considered here, heating by dipole force fluctuations [9,10] is much smaller than recoil heating.) In the first demonstration of dipole trapping, the detuning was about 1.5 nm and τ_h was a few milliseconds; this heating was overcome with additional cooling with optical molasses [1]. A relatively shallow trap with a detuning of up to 6 nm has been demonstrated [8].

We load the atoms into the FORT from a vapor cell magneto-optic trap (MOT) [11]. The magneto-optic trap consists of three pairs of counterpropagating, $\sigma^+-\sigma^-$ laser beams, which intersect at right angles inside a Rb vapor cell at the zero-field point of a magnetic spherical quadrupole [2,11]. The ^{85}Rb atoms have two ground-state ($5\,^2S_{1/2}$) hyperfine levels with $F=2$ and 3 separated by 3.04 GHz, and $5\,^2P_{1/2,3/2}$ excited states with $\Gamma=3.7\times10^7$ s^{-1}. The laser beams are tuned $(1-3)\,\Gamma$ below the ^{85}Rb $5\,^2S_{1/2}(F=3)\leftrightarrow5\,^2P_{3/2}(F=4)$ transition at 780 nm, and have a spot size of 0.67 cm and a total six-beam intensity of 26 mW/cm^2. A "repumping" laser tuned to the $5\,^2S_{1/2}(F=2)\leftrightarrow5\,^2P_{3/2}(F=3)$ transition intersects the same region, preventing optical pumping into $5\,^2S_{1/2}(F=2)$. The Rb pressure in the vapor cell is about 4×10^{-8} Torr and the magnetic-field gradient is 15 G/cm.

The FORT consists of a single, linearly polarized, focused Gaussian laser beam, of wavelength λ tuned between 4 and 67 nm to the red of the ^{85}Rb $5\,^2S_{1/2}-5\,^2P_{1/2}$ ($D1$ transition) at 795 nm. The TEM$_{00}$-mode beam is usually chopped at about 200 kHz, contains $P=0.6$ to 0.9 W of time-averaged power, and has a waist size of $w_0=9.6\pm1$ μm. Typical parameters for the dipole trap at a wavelength $\lambda=814.0$ nm and power 0.80 W are a well depth of $U_0/k_B=6.0$ mK, peak photon scatter rate at the beam waist $\gamma_{s0}=4.0\times10^2$ s^{-1}, and a recoil heating trap lifetime of $\tau_h=43$ s. The corresponding ac Stark shift at the beam waist of 125 MHz is independent of the ground-state sublevel. A circularly polarized probe laser beam at the same frequency as the MOT beams intersects the FORT beam waist, where a 150-μm-diam region is

imaged onto a photomultiplier tube. Each laser beam may be on, off, or chopped by an acousto-optic shutter. The saturated trap fluorescence signal from the probe beam is used to determine the number of trapped atoms, to a fractional accuracy of ±30%. We can determine either the total number of atoms, or the number of atoms in the $F=3$ ground-state sublevel only, depending on whether the repumping laser is on or off during the probe fluorescence measurement.

To load atoms from the MOT into the FORT, we begin with both MOT and FORT laser beams chopped at about 200 kHz, alternating with each other. Alternating the beams is not necessary for shallow traps [8]. However, we are interested in strongly confining traps, for which the alternation prevents the ac Stark shift of the FORT beam from shifting the atoms out of resonance with the MOT beams [1]. The MOT cools and traps atoms from the room-temperature vapor in the cell [11], and (being chopped) typically contains 10^6 atoms at a density of 10^{10} cm^{-3} and a temperature of 160 μK. In one loading method, we intersect the FORT beam with the MOT, and atoms that wander into the FORT are cooled further and become trapped there. Then, the MOT is turned off and untrapped atoms quickly disperse and fall away due to gravity. At $\lambda=814$ nm, up to 10^4 atoms can be loaded into the FORT in this way. We can also load the FORT from the expanding cloud of optical molasses [12,13], which is obtained when the magnetic-field gradient is turned off. In this case, about 1300 atoms are typically loaded when the FORT is within several millimeters of the MOT, at $\lambda=814$ nm. The number of atoms loaded falls by about a factor of 2 between $\lambda=814$ and 860 nm, and then falls rapidly for larger detunings.

The lifetime of the trapped atoms as a function of trapping laser wavelength is illustrated in Fig. 1. For these measurements, we load atoms into the trap, then allow them to evolve freely in the dipole trap with no additional cooling for a variable delay time, and finally probe the number of atoms remaining. We determine the lifetime at each wavelength from an exponential fit to the resulting decay curve. The long lifetimes observed beyond 811 nm depend on Rb background-gas pressure and are consistent with loss due to collisions with background-gas atoms in our vapor cell. Trapping is obtained out to a detuning from the lowest Rb resonance of more than 65 nm.

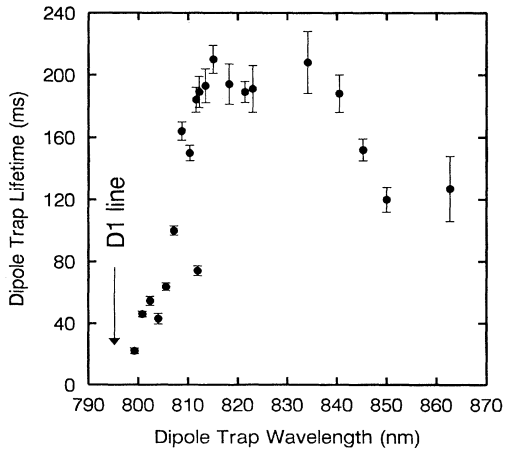

FIG. 1. Trap lifetime of atoms in the FORT as a function of FORT laser beam wavelength. Error bars are standard deviations from the exponential fit to individual decay curves. Lifetimes of $\tau_c \approx 200$ ms are expected for the background-gas pressure in the vapor cell. The short lifetimes between $\lambda=799$ nm and $\lambda=810$ nm are not due to heating atoms out of the trap, since τ_h is greater than 10 s for all detunings shown.

Shorter lifetimes are measured for trapping laser wavelengths between $\lambda=799$ and 811 nm. These lifetimes do not depend on Rb background-gas pressure, and are not due to dipole trap heating [9,10]. A density-dependent loss mechanism [6] for these larger decay rates is not ruled out by the data. However, the short lifetimes are probably not associated with hyperfine changing collisions between trapped atoms [6] because they display a sharp dependence on λ. A radiative collisional mechanism similar to cold-atom photoassociation [14] may be responsible for the short decay times. A detailed study of the loss rate versus density, laser intensity, and wavelength, in progress, should elucidate the trap-loss mechanism. For example, loss due to collisions between trapped atoms should display a rate proportional to density; loss associated with multiphoton ionization would display a nonlinear dependence on laser intensity.

Recoil heating rates in the FORT are too small to measure directly within the time limit imposed by collisional loss. However, we have indirectly measured the scattering rate $\gamma_{s0}=\tau_{s0}^{-1}$ of atoms trapped in the FORT. Atoms in the dipole trap are initially pumped into the $F=2$ ground-state hyperfine level, and then allowed to evolve in the unchopped dipole trap with no additional beams present. We then measure the population of the $F=3$ ground-state hyperfine level as a function of trapping time, as shown in Fig. 2 for $\lambda=806.6$ nm and $P=1.26$ W. Spontaneous Raman scattering from the trapping beam gradually redistributes the atoms between the ground-state sublevels, causing the $F=3$ population to increase with a time constant τ_{eq}. We calculate [15] that $\tau_{eq}=4.78\tau_{s0}$ at $\lambda=806.6$ nm. From the measured value of $\tau_{eq}=2.9\pm0.1$ ms, we therefore infer that $\tau_{s0}=0.61\pm0.02$ ms. This is in good agreement with the value $\tau_{s0}^{(calc)}=0.71\pm0.13$ ms calculated for our laser intensity and detuning. This photon scatter rate corresponds

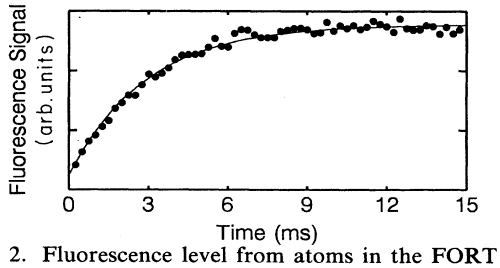

FIG. 2. Fluorescence level from atoms in the FORT in the $F=3$ ground-state hyperfine level as a function of time after being optically pumped into the $F=2$ ground-state hyperfine level. The increase in fluorescence is due to spontaneous Raman scattering from the FORT laser, which transfers atoms from $F=2$ to $F=3$. The fitted curve is an exponential with mean-life $\tau_{eq}=2.9\pm0.1$ ms, and the experimental parameters are $P=1.26$ W and $\lambda=806.6$ nm.

to a heating rate of only 0.57 mK/s, and to a trap lifetime of $\tau_h = 24$ s. We observe scattering rates as small as 0.2 photons/ms at the larger detunings, which are limited by scattering of near resonant light from the probe and MOT beams, which is not completely extinguished by our acousto-optic shutters.

We have also determined the temperature of the atoms in the FORT by measuring the Doppler broadening of a stimulated Raman transition induced by counterpropagating beams [16]. The Raman beams are oriented either parallel or perpendicular to the trap axis, yielding either axial or radial temperatures, respectively. For this measurement, the atoms are suddenly (compared to the trap oscillation period) released from the dipole trap and optically pumped into the $F=2$ state. We then drive the $F=2$ to $F=3$ stimulated Raman transition, and measure the resulting population of $F=3$ atoms versus the difference frequency between the two beams. A typical axial Raman resonance is shown in Fig. 3.

The temperature T_r of the atoms in the radial direction is found to be between 0.35 and 0.4 mK at $\lambda=814$ nm and $P=0.8$ W. This corresponds to a Gaussian distribution of density in the radial direction with a $1/e$ radius of $r_0=(2k_BT_r/m\omega_r^2)^{1/2}=1.75$ μm, where $\omega_r=(4U_0/mw_0^2)^{1/2}=2\pi\times 25$ kHz is the radial oscillation frequency of the trapped atoms. We find that we can reduce T_r to temperatures of only 0.23 mK by alternating the trap with polarization gradient molasses [13], even though we cool free atoms in the same molasses to temperatures as low as 7 μK. We obtained lower temperatures in weaker traps; for example, $T_r=0.14$ mK with $\lambda=822$ nm and $P=0.35$ W ($U_0/k_B=2.0$ mK).

The temperature of the atoms T_z in the axial direction is measured to be in the range from 0.5 to 2.2 mK, for $\lambda=814$ nm and $P=0.8$ W. We typically measure the temperature 25 ms after loading, which is shorter than the time $\tau_c\sim 0.1$ s for which we expect elastic collisions to equilibrate T_z and T_r [17]. The higher axial temperatures appear to be due to inhomogeneous forces acting within the cooling beams, which are also responsible for spatial irregularities in the density of our MOT [18]. During the loading phase, atoms in the FORT are in equilibrium between the optical dipole force from the FORT and forces from the cooling beams. Along the axis of the FORT these forces can be comparable,

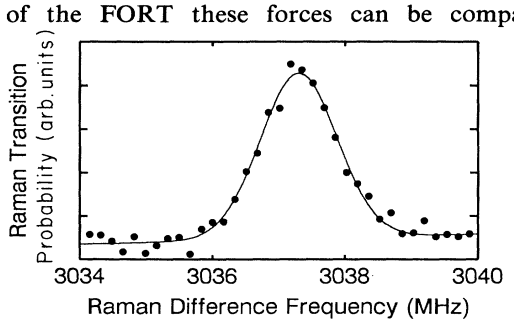

FIG. 3. Stimulated Raman transition probability between the ^{85}Rb hyperfine levels, as a function of the difference frequency between the two beams inducing the transition. For these data the beams counterpropagated along the axis of the dipole trap. The fitted curve is a Gaussian of width 1.37 MHz. From this Doppler width we infer a temperature $T_z=0.53\pm 0.03$ mK.

preventing atoms from reaching thermal equilibrium with the optical potential of the FORT. These temperatures are consistent with the observed trap lengths of 150 to 500 μm. The shortest traps and lowest temperatures are consistent with a thermal equilibrium with $T_z\approx T_r$, and can be obtained by alternating the loaded trap with low-intensity optical molasses [12,13]. When the FORT is loaded from optical molasses it is also possible to adjust the alignment of the laser beams to produce a small region where the forces within the molasses are nearly balanced. In this case we also obtained short traps with $T_z\approx T_r$.

The peak density n_0 of the trapped atoms can be determined from the measured number and temperature of trapped atoms. For a trap with $T_z\approx T_r=0.4$ mK, $\lambda=814$ nm, and $P=0.8$ W, we load $N=1300$ atoms, giving $n_0=(2N\lambda/\pi w_0^4)(U_0/\pi k_BT)^{3/2}=8\times 10^{11}$ cm^{-3}. Up to 10^4 atoms can be loaded at this λ and P, with a peak density of about 2×10^{12} cm^{-3}, but the atoms are then distributed over 500–600 μm in length. These densities are below the density limit from repulsive rescattering forces [7], which we estimate to be about 10^{13} cm^{-3} for our loading conditions at this λ and P.

In summary, we have observed confinement of atoms in a stable optical trap operating up to 65 nm off resonance. We have measured trap lifetimes limited by background-gas collisions, and also measured extremely low scatter rates and heating. This trap should be useful for obtaining high densities of trapped atoms. This is because atoms trapped in a FORT can be cooled slowly, without a large fraction of excited-state atoms, so that density-limiting mechanisms such as rescattering of photons [7] and trap loss due to excited-state collisions [6] are reduced. It may be possible to confine microkelvin temperature atoms in a dipole trap at large detunings [8]; however, an efficient way to cool the *trapped* atoms must be demonstrated [8,19,20].

The combination of strong confinement and a low photon scattering rate of the FORT makes it well suited to a variety of experiments. For example, it can have an oscillation frequency $\omega_r \gg R/\hbar$ and at the same time have a heating rate that is much less than one vibrational quantum per period of oscillation. In this case it should be possible to cool atoms into the quantum ground state of the trap with Raman sideband cooling [19,20]. This technique is applicable to trapped atoms because Raman transitions between ground-state sublevels can be unperturbed by the optical dipole potential [20]. Quantum optics experiments could be carried out on an "atomic point sample" consisting of a small number of atoms confined to subwavelength dimensions. Because scatter rates are so low, the experiments could be carried out on the *trapped* atoms. Finally, because the FORT can confine ground-state atoms in a well-defined, arbitrary spin state, it should be ideal for studies of state-selective collisions and collective phenomena.

This work is supported by the National Science Foundation. D. J. H. received support from the Alfred P. Sloan Research Foundation. We thank W. D. Phillips, P. Lett, and K. Helmerson for informative discussions.

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