Spin relaxation of optically trapped atoms by light scattering

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We study spin relaxation of optically trapped atoms that is due to light scattering from the trap laser. We observe relaxation times greater than 2 s for ground-state hyperfine-level populations of ^{85}Rb atoms trapped in an optical dipole force trap operating as much as 65 nm to the red of the $D1$ line. The measured relaxation rate can be more than 100 times slower than the atoms' total spontaneous scatter rate from the trap laser. This enhancement in atomic ground-state lifetime is due to an interference effect in spontaneous Raman scattering far from atomic resonance.

Atom trapping has attracted much interest recently,[1,2] partly because of the possibility of experiments having extremely long observation times. Experimental studies of ultracold atomic collisions,[3,4] collective effects,[4,5] and precise spectroscopy[6,7] would all benefit from an increase in the time that atoms are available for measurement. Although confinement times for trapped atoms can be long, the useful measurement time is often limited by the relaxation time of atomic populations and coherences. This relaxation can increase trap loss rates, interrupt cooling processes, increase resonance linewidths, or prevent state-selective experiments. Thus internal atomic relaxation times are an extremely important characteristic of atom traps.

Magnetic atom traps[1,4,5,8] have long relaxation times but have the disadvantages that they are relatively weak, confine only a limited number of atomic states, and perturb the resonance frequencies between the trapped states. Atomic fountains[7] are useful for certain experiments, but there is an upper limit to observation time set by practical limits on apparatus size and on the gravitational acceleration of atoms. Optical traps such as the magneto-optical trap[9,10] (MOT), which rely on the scattering force for confinement, have proved extremely useful but suffer from short relaxation times because the high rate of spontaneous photon scattering from the trap laser quickly randomizes atomic variables. The optical dipole force trap,[11] however, can confine atoms with a much-reduced photon scatter rate. It can strongly trap all atomic ground states and can leave ground-state hyperfine or Zeeman resonance frequencies nearly unperturbed.

We study the relaxation rate of ground-state hyperfine-level populations of ^{85}Rb atoms trapped in a far-off-resonance optical dipole force trap.[12,13] The relaxation rate is reduced because the spontaneous photon scatter rate is slow far from atomic resonance. In addition, we find an enhancement in atomic ground-state lifetime that is due to an interference effect in spontaneous Raman scattering far from resonance. Because of this we observe relaxation times longer than 2 s, more than 100 times longer than the mean time between photon scattering events for a single atom. The results of our study apply to the relaxation of any ground-state degree of freedom, including coherence. To our knowledge this aspect of the dipole force atom trap has never been discussed.

Figure 1 shows the relevant energy levels of ^{85}Rb. The dipole force trap laser wavelength λ_L is always more red than both D lines, between 798 and 860 nm. The trap consists of a single linearly polarized Gaussian laser beam containing either a power $P = 1.60 \pm 0.06$ W focused to a waist $w_0 = 11.4 \pm 0.8$ μm or $P = 1.00 \pm 0.06$ W and $w_0 = 9.0 \pm 0.6$ μm, either of which produces a peak intensity of 0.79 ± 0.11 MW/cm^2. The ac Stark shift experienced by ground-state atoms produces a potential well with a depth between 3 and 30 mK.

The dipole force trap is loaded with ultracold atoms from a MOT.[9] Experimental details about the MOT and the loading process were discussed previously.[13] The MOT laser frequency is 10 MHz to the red of the $5S_{1/2}(F = 3)$–$5P_{3/2}(F' = 4)$ transition. A probe beam is derived from the same laser for laser-induced

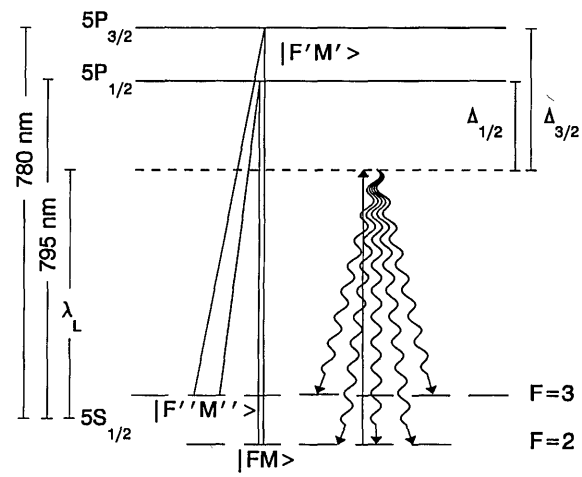

Fig. 1. Energy levels of ^{85}Rb showing spontaneous transitions from a linearly polarized laser. The ground-state hyperfine splitting is 3 GHz, and the excited-state hyperfine splitting, not shown, is of the order of 0.3 GHz. The laser wavelength λ_L is always to the red of both D lines, between 798 and 860 nm. For laser detunings greater than the excited-state fine- or hyperfine-structure splitting the scattering process can follow more than one path, as indicated by the solid lines.

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fluorescence measurements. An optical repumping laser prevents optical pumping into the $5S_{1/2}(F = 2)$ hyperfine level while the MOT is operating.

The experiment monitors the population of the upper hyperfine level of the ground state ($F = 3$) as a function of time after the entire population is transferred into the lower hyperfine level of the ground state ($F = 2$). First, we load atoms into the dipole force trap from the MOT by intersecting the two traps and alternating them in time at a frequency of 200 kHz for 200 ms. This procedure loads the dipole force trap with $\sim N = 2500$ atoms at a temperature of ~0.5 mK. Second, while the trap beams are still being alternated, the optical repumping laser is turned off for 40 ms. Atoms that were trapped in the MOT fall away as a result of gravity, and atoms that are trapped in the dipole force trap are all optically pumped into $F = 2$. Third, the dipole force trap is turned on continuously, and all other laser beams are turned off. This continues for a variable delay time t during which the ground-state hyperfine-level populations relax because of light scattering from the dipole force trap laser. Fourth, after the variable delay time, the dipole force trap is turned off, and the probe laser beam, resonant with $F = 3$, is turned on. The laser-induced fluorescence signal is proportional to N_3, the population of atoms having $F = 3$. Alternatively, we can determine the total ground-state population N by also turning on the optical repumping laser, resonant with $F = 2$, at this time. This four-step process is repeated for a range of delay times t, and then the entire range of times is repeated five or ten times and averaged. This procedure is performed for different trap laser wavelengths.

The experimental data $N_3(t)/N(t)$ shown previously[13] are well fitted by the function $f[1 - \exp(-t/\tau_{\mathrm{rel}})]$, where f is the fraction of atoms having $F = 3$ at long times and τ_{rel} is the experimental relaxation time. The error in τ_{rel} from the fit is ~10%. The normalization to $N(t)$ is essential for the longest relaxation time measurements because the total population of atoms in the trap decays with a lifetime of $\tau_{\mathrm{coll}} = 3$ s because of loss from background gas collisions. In order to observe the longest relaxation times, it was necessary to eliminate several unwanted sources of light scattering in the experiment that increased the relaxation rate: stray light from the near-resonance MOT laser and probe beams, and the on-resonance fraction of the broadband radiation emitted by the Ti:sapphire dipole force trap laser and by the ionization gauge inside the vacuum chamber.

Figure 2 shows the measured relaxation times τ_{rel} that span 4 orders of magnitude, from 0.16 ms to 2.1 s. The dashed curve labeled τ_s shows the calculated mean time between spontaneous scattering events. The measured relaxation rates are much slower than the total photon scatter rate because of an interference effect in spontaneous Raman scattering far from resonance.

Figure 1 shows the possible transitions when an atom spontaneously scatters a photon from a linearly polarized laser with a frequency far from atomic resonance. Rayleigh scattering occurs when an atom returns to the same state after a spontaneous scattering event. Raman scattering occurs when the final state and the initial state are different, even though the states may be degenerate in energy. The present experiment is sensitive to only spontaneous Raman scattering events that change F.

If the laser frequency ω_L is nearly resonant with a transition between an initial ground state $|FM\rangle$ and an intermediate excited state $|F'M'\rangle$, then the rate $\gamma_{FM\to F''M''}$ of spontaneous transitions from the ground state $|FM\rangle$ to the ground state $|F''M''\rangle$ is simply proportional to $|\langle F''M''|\mu_q|F'M'\rangle\langle F'M'|\mu_0|FM\rangle|^2$. F is the atom's total angular momentum, M is its projection onto the z axis, which is chosen along the laser's electric-field vector, and μ_q is the spherical component of the electric-dipole moment operator, with $q = -1$, 0, or 1. If, however, the laser detuning is comparable with or larger than the splitting between excited states, a particular intermediate state is not selected during the scattering process. In this case we must sum the amplitudes for all possible paths for the scattering process before squaring to find the spontaneous transition rate. Using the Kramers–Heisenberg formula,[14] we have

$$\gamma_{FM\to F''M''} = \frac{3\pi c^2 \omega_L{}^3 I}{2h\mu^4}\left|\frac{a^{(1/2)}_{FM\to F''M''}}{\Delta_{1/2}} + \frac{a^{(3/2)}_{FM\to F''M''}}{\Delta_{3/2}}\right|^2, \tag{1}$$

where $\Delta_{J'} = \omega_L - \omega_{J'}$ and

$$a^{(J')}_{FM\to F''M''} = \frac{\Gamma_{J'}}{\omega^3_{J'}} \sum_{q,F',M'} \langle F''M''|\mu_q|F'M'\rangle\langle F'M'|\mu_0|FM\rangle, \tag{2}$$

where the sum over F' includes only those states within the $5P_{J'}$ level. $\hbar\omega_{J'}$ and $\Gamma_{J'}$ are the energy and spontaneous decay rate of the $5P_{J'}$ states, and $\mu = \langle 33|\mu_{-1}|44\rangle$. $a^{(J')}_{FM\to F''M''}/\Delta_{J'}$ are the amplitudes for a spontaneous scattering path through the intermediate states within the $5P_{J'}$ levels, indicated by the two solid lines in Fig. 1. Ignoring, for the

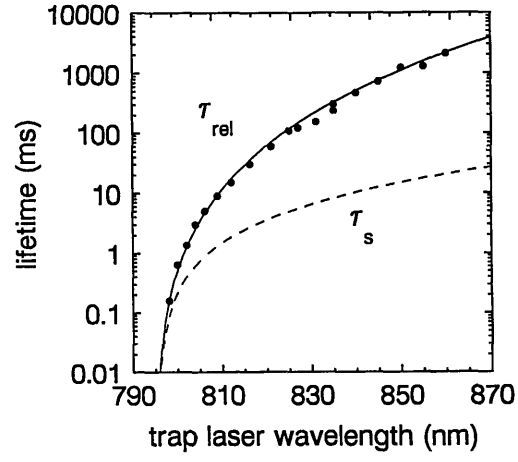

Fig. 2. Hyperfine population relaxation time as a function of trap laser wavelength. Experimental measurements are shown as filled circles. Calculated relaxation times are shown by the solid curve. The calculated mean time between spontaneous photon scattering events is shown by the dashed curve.

moment, the dependence of $\omega_{J'}$ and $\Gamma_{J'}$ on J', we calculate the sum in Eq. (2). The result is that, for $FM \neq F''M''$ (Raman scattering), $a^{(3/2)}_{FM\to F''M''} = -a^{(1/2)}_{FM\to F''M''}$, whereas for $FM = F''M''$ (Rayleigh scattering), $a^{(3/2)}_{FM\to FM} = 2a^{(1/2)}_{FM\to FM}$. Substituting these relations into Eq. (1), we see that, for extremely large detunings, where $\Delta_{3/2} \approx \Delta_{1/2}$, the amplitudes for Raman scattering cancel almost exactly, whereas the amplitudes for Rayleigh scattering add together. The consequence is that Raman scattering occurs at a much slower rate ($\sim 1/\Delta^4$) than the total spontaneous scatter rate ($\sim 1/\Delta^2$). A simple explanation is that a change of spin during spontaneous scattering can occur only through the fine-structure interaction $\mathbf{L}\cdot\mathbf{S}$ between orbital and spin angular momenta during the time $1/\Delta$ the atom spends in the excited state, because the atom–field interaction depends on the motion of the electron and not on its spin in the electric dipole approximation. Another view is that populations and coherences are transferred nearly completely between ground and excited states during the scattering cycle, similar to the partial preservation of coherence observed in optical pumping experiments near resonance.[15] We note that the recoil heating rate[11] is proportional to the total spontaneous scattering rate, not to the slower relaxation rate.

To compare experiment with theory, we calculate the rate $\gamma_{F\to F''}$ for an atom to make a transition between hyperfine levels F and F'' by averaging $\gamma_{FM\to F''M''}$ over initial M levels and summing over final M'' levels. By use of a rate equation treatment, the relaxation rate of the hyperfine-level populations N_2 and N_3 is $\gamma_{\mathrm{rel}} = \gamma_{2\to 3} + \gamma_{3\to 2}$, and the total spontaneous scatter rate is $\gamma_s = \gamma_{2\to 2} + \gamma_{2\to 3} = \gamma_{3\to 2} + \gamma_{3\to 3}$. In Fig. 2 we show $\tau_{\mathrm{rel}} = \gamma_{\mathrm{rel}}^{-1}$ as a solid curve and $\tau_s = \gamma_s^{-1}$ as a solid curve. Excellent agreement between theory and experiment is obtained with no adjustable parameters.

A number of approximations and assumptions were made in the calculation of τ_{rel}. We neglect counter-rotating terms in Eq. (1) that change τ_s by 10% at the longest experimental wavelength but produce a negligible change in τ_{rel}. We assume that the initial population of Zeeman sublevels is isotropic since the MOT laser polarization has all possible directions within the trap. We also neglect alignment that is due to optical pumping during spontaneous scattering, which is calculated to change τ_{rel} by only 1%. The spatially averaged intensity experienced by the atoms as a result of their nonzero temperature, ~90% of the peak intensity, is used in the calculation. If the temperature of the atoms and the trap laser beam power are known, then the measured τ_{rel} can be used to determine the beam waist, which is difficult to measure accurately by use of standard techniques.

In summary, we have observed relaxation times longer than 2 s for internal variables of ultracold atoms. We measure relaxation rates much slower than the total spontaneous photon scatter rate, in good agreement with theoretical predictions of an interference effect in spontaneous Raman scattering. Although this experiment was concerned mainly with relaxation of hyperfine-level populations, we also expect long relaxation times for Zeeman-sublevel populations and for hyperfine and Zeeman coherences. This means that spin polarization of the trapped atoms can be easily maintained with weak optical pumping. We note that a blue-detuned dipole force trap operating several hundred nanometers from resonance would confine atoms at an intensity minimum, producing exceedingly small relaxation rates that would be attractive for precision hyperfine or Zeeman resonance experiments. Because of its extremely slow relaxation rate, the far-off-resonance dipole force trap is ideal for a variety of experimental studies of precise spectroscopy, ultracold collisions, and collective effects.

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