Laser Cooling without Repumping: A Magneto-Optical Trap for Erbium Atoms

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We report on a novel mechanism that allows for strong laser cooling of atoms that do not have a closed cycling transition. This mechanism is observed in a magneto-optical trap (MOT) for erbium, an atom with a very complex energy level structure with multiple pathways for optical-pumping losses. We observe surprisingly high trap populations of over 10^6 atoms and densities of over 10^{11} atoms cm^{-3}, despite the many potential loss channels. A model based on recycling of metastable and ground state atoms held in the quadrupole magnetic field of the trap explains the high trap population, and agrees well with time-dependent measurements of MOT fluorescence. The demonstration of trapping of a rare-earth atom such as erbium opens a wide range of new possibilities for practical applications and fundamental studies with cold atoms.

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The use of laser light in combination with a quadrupole magnetic field to capture and cool atoms into a magneto-optical trap (MOT) has become one of the most ubiquitous tools in atomic physics over the past two decades, leading to fundamental discoveries and practical applications in such diverse fields as quantum degenerate gases, cold collisions, quantum information processing, ultraprecise frequency standards, quantum optics, and trace atom detection. In forming a MOT, one of the most important and widely agreed upon fundamental requirements is the need for a closed, or nearly closed, optical-pumping cycle. That is, it is assumed necessary for the atom to have an optical transition that can be excited repeatedly without significant loss of population via optical pumping to one or more energy levels that do not interact with the laser. If loss does occur, this usually must be compensated for by introducing one or more auxiliary lasers that keep the atoms scattering photons. For this reason, laser cooling and trapping has been restricted to alkalis, alkaline earths, metastable rare gases, and a few other atoms where repumping has proven feasible [1]. Large sections of the periodic table have been considered off-limits to magneto-optical trapping because of the perceived ''optical leak'' problem.

In this Letter, we describe the formation of a robust magneto-optical trap for erbium atoms with a population of over 10^6 atoms and a density of over 10^{11} cm^{-3}, despite the existence of numerous optical leak channels, none of which are repumped by auxiliary laser beams. We present evidence for the existence of a recycling mechanism that explains the surprisingly high trap population, and discuss a rate equation model that describes this mechanism. Our model agrees extremely well with trap decay measurements, and allows us to extract key transition rates associated with the various pathways in the recycling process.

In addition to uncovering a novel recycling process that lifts the requirement for a closed optical transition, the demonstration of a magneto-optical trap for erbium atoms opens a wide range of new possibilities for applications of cold atoms. For example, a recent study [2] has shown that erbium has several other potential laser cooling transitions at convenient wavelengths that are completely closed to optical-pumping leaks. These offer opportunities for extremely low laser cooling temperatures (for example, the transition at 841 nm has a recoil limit of 81 nK) and the creation of a two-level atomic system with a wavelength in the technologically significant 1.3 μm region. Also, the $4f^{12}6s^2(^3H_6)$ configuration of the erbium ground state with its large orbital angular momentum and very high magnetic moment of $7\mu_B$ enables new studies in areas such as orbital effects in ultracold collisions, and Bose-Einstein condensation with dipolar gases [3]. Further extensions include the possibility of deterministic single atom sources [4], as well as working with other rare earths such as Dy and Ho, which have similar atomic level structure, but different ground state spin configurations and isotope distributions.

An energy level diagram [5] for neutral Er is shown in Fig. 1(a), where the levels up to the laser cooling level at 24 943.272 cm^{-1} are plotted vs J value, and even and odd parity are indicated by black and gray (red online) lines, respectively. The figure shows that there are 110 levels (33 even and 77 odd), with J values ranging from 2 to 12, located in the energy gap between the ground and excited states of the cooling transition. In principle, all of these levels represent potential optical-pumping dead ends. Because of dipole optical selection rules, however, the strongest decay channels from the laser-excited level will be to any level with even parity and J value of 6, 7, or 8. From the 19 such levels, further decay can occur to $J = 5$, 6, 7, 8, 9 odd-parity levels. This cascading can continue until atoms are eventually stuck in a very long-lived metastable state, or find their way back to the ground state.

Considering the number of possible cascade pathways, and the fact that none of the interlevel transition probabilities are known with any certainty at all, it is virtually

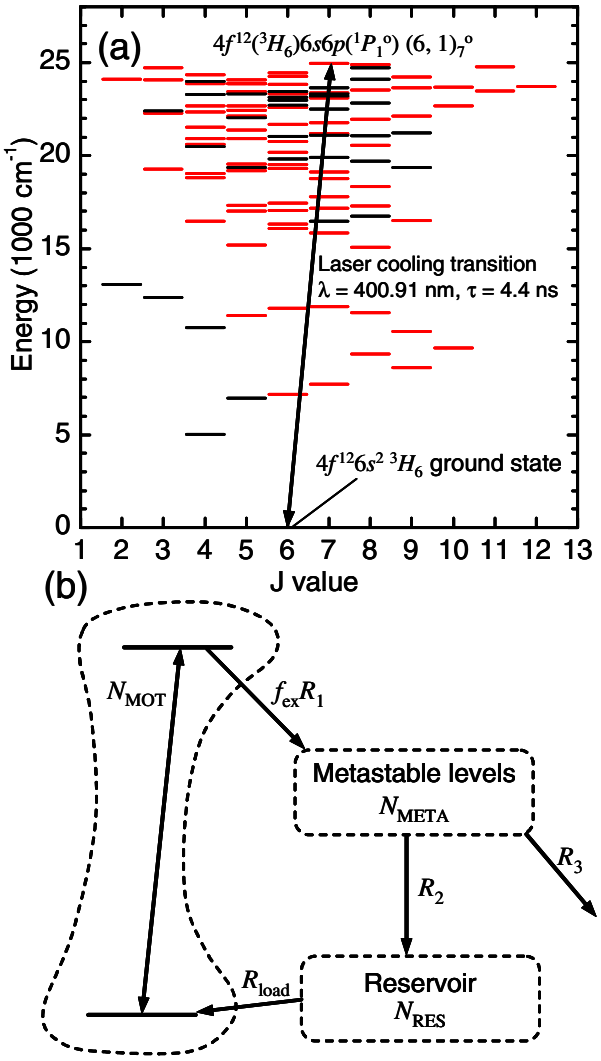

FIG. 1 (color online). (a) Energy levels of erbium vs J value, showing the laser cooling transition and the many metastable levels. Odd parity is indicated by gray lines (red online). (b) Schematic of the recycling model described by Eq. (1). Atoms decay from the MOT with effective rate $f_{ex}R_1$ to a manifold of metastable levels. Atoms are either lost from the metastable manifold with a rate R_3, or decay to the ground state with rate R_2 to form a reservoir of atoms held by the quadrupole magnetic field of the MOT. Reloading of the MOT occurs from the reservoir with a rate R_{load}.

impossible to calculate the cascading process and thereby predict the degree to which optical pumping to metastable states will affect the performance of a MOT. Based on comparison with a few known transition rates involving similar configuration changes in Er and other rare earths, the best one can do is guess that most of the dipole-allowed transitions will have rates in the 10^3 s^{-1} to 10^5 s^{-1} range [2]. This sort of transition rate, combined with the number of possible decay channels, suggests a very pessimistic outlook for the formation of a MOT.

Our Er magneto-optical trap was formed with a quadrupole field produced by a pair of anti-Helmoltz coils and 3 pairs of counter-propagating, circularly polarized laser beams [6]. The laser light was tuned to the red of the very strong $4f^{12}6s^2(^3H_6) \rightarrow 4f^{12}(^3H_6)6s6p(^1P_1^o)(6, 1)_7^o$ transition at 400.91 nm (vacuum wavelength), which has a natural lifetime of $\tau = 1/\Gamma = 4.5$ ns [7]. The detuning was chosen based on maximum MOT fluorescence signal, which occurred at approximately 0.7Γ. We note that this detuning is significantly smaller than the optimum found in more conventional MOTs, and we believe this is because optimization of the recycling mechanism discussed below influences the overall optimum detuning. The magnetic field gradients were typically 0.28 T/m (axial) and 0.135 T/m (radial), and the laser beams had $1/e^2$ diameters of (5.9 ± 0.1) mm (axial) and (6.6 ± 0.1) mm (radial) [8]. Power in the beams was variable, with a maximum value of about 11 mW in each of the radial beams and 3.6 mW in the axial beams. An erbium atomic beam was produced in an effusive cell with a 1 mm diameter orifice, operating at 1350 °C, and a σ^- Zeeman slower [9] with a length of about 30 cm was used to load the MOT. The vacuum system, pumped by two ion pumps, had a pressure of about 1.3×10^{-6} Pa.

The 401 nm laser light for the MOT and the slower was produced by a frequency-doubled single-frequency, stabilized Ti:sapphire laser operating at 802 nm. The output of the doubler was directed into a series of acousto-optic modulators used as splitters and switches that resulted in independently gateable MOT light and slower light, with the slower light always tuned 525 MHz below the MOT light. Locking of the laser frequency at a fixed detuning relative to the atomic transition was achieved via a probe beam crossing the atom beam near the oven [10]. Fluorescence light from the MOT was collected with a pair of plano-convex 50 mm diameter lenses and focused onto a Si photodiode detector, and a charge-coupled device camera with 2.4× optics was used to obtain images of the fluorescent cloud.

With this experimental setup, MOT populations as high as $(1.6 \pm 0.3) \times 10^6$ atoms and atomic densities as high as $(3.4 \pm 0.9) \times 10^{11}$ cm^{-3} were observed. Traps containing the isotopes ^{164}Er, ^{166}Er, ^{167}Er, ^{168}Er, and ^{170}Er, were all seen; the measurements discussed here were done with ^{168}Er, which had the largest signal. The MOT population was derived from the observed fluorescence intensity together with estimations of photon detection efficiency and excited state fraction, and the density was obtained from measurements of the area occupied by a CCD image of the MOT. MOT diameters ranged from 100 to 130 μm, a size that is relatively small and probably due at least in part to additional magnetostatic confinement forces from the quadrupole field. Details of the methods used to derive the population and density are contained in Ref. [11]. The uncertainties represent the combined uncertainties of laser power and beam diameter measurement, detuning calibration, detection efficiency, and saturation correction factor [12]. The density has an additional uncertainty component arising from the assumption of a spherical, Gaussian MOT.

We believe the explanation for why a significant MOT population can be obtained with Er, despite the many optical leaks, lies in the large J values of nearly all the states of Er. As atoms in the MOT decay to metastable states, they no longer feel the light pressure of the MOT beams and begin to diffuse out of the MOT region. Many of these atoms, however, have a large enough magnetic moment to be held by the quadrupole magnetic field of the trap, so they remain in the vicinity. Eventually, a large fraction of the metastable atoms cascade back to the ground state, forming a reservoir that can be recycled into the MOT. With this recycling process, the total MOT population is governed only by the net loss rate of metastable atoms from the magnetic trap, not by the spontaneous decay rate from the excited state. As this metastable loss rate can be relatively slow, a large MOT population can build up.

Because it is virtually impossible to model the full cascade process exactly, we have chosen to construct a model, illustrated in Fig. 1(b), that contains the essential elements of the MOT loading, cascading, recycling and loss processes. We consider three populations: (1) the number of atoms in the MOT, N_{MOT}, including both ground and excited states; (2) the aggregate number of atoms in all the metastable states, N_{META}; and (3) the number of atoms in the ground state that are held in the magnetic quadrupole field reservoir outside the MOT, N_{RES}. With these definitions, we write a set of rate equations governing the time dependence of these populations:

$$\begin{aligned} \dot{N}_{\mathrm{MOT}} &= R_{\mathrm{load}} N_{\mathrm{RES}} - f_{\mathrm{ex}} R_1 N_{\mathrm{MOT}}, \\ \dot{N}_{\mathrm{META}} &= f_{\mathrm{ex}} R_1 N_{\mathrm{MOT}} - (R_2 + R_3) N_{\mathrm{META}}, \\ \dot{N}_{\mathrm{RES}} &= -R_{\mathrm{load}} N_{\mathrm{RES}} + R_2 N_{\mathrm{META}}, \end{aligned} \tag{1}$$

where R_{load} is the load rate (per atom) of the MOT from the quadrupole trap, f_{ex} is the fraction of excited state atoms in the MOT, R_1 is an effective net transition rate (per atom) out of the excited state to all the metastable states, R_2 is an effective net transition rate (per atom) from all the metastable states to the ground state, and R_3 is an effective rate (per atom) for loss from the metastable states. Equation (1) does not include external loading from the slower, because that is the situation in the experiments discussed below. Also, the loss due to background gas collisions is ignored because this rate ($\approx 0.5\ \mathrm{s}^{-1}$ or less) is much smaller than the other rates in the model. Furthermore, we note that the net transition rate from the MOT to the metastable levels is proportional to the effective transition rate out of the excited state R_1 multiplied by the excited state fraction f_{ex}, since the atoms can only make this transition if they are in the excited state.

To test the validity of our model, and also to make a determination of the relevant rates R_1, R_2, and R_3, we conducted a series of measurements of the transient behavior of the MOT fluorescence at 20 different values of the power and detuning of the MOT light. In the time sequence of an experiment, the MOT was allowed to reach steady state for a few seconds, and then both the MOT light and the slower light were turned off for 0.2 s. This allowed any transient loading from the slower to decay and ensured an initial condition of $N_{\mathrm{MOT}} = 0$. Then the MOT light was turned on and the time dependence of the fluorescence was recorded. A typical measurement is shown in Fig. 2, where good qualitative support for our model is visible. When the MOT light is first turned on, the fluorescence rises rapidly to nearly 100% of the value it had in the steady state, indicating recapture of population from the reservoir. After peaking, the fluorescence shows a clear two-component exponential decay, consistent with a rate equation system such as Eq. (1) with several decay components. We should note that the time dependence seen in Fig. 2 is not consistent with the sort of decay observed in MOTs with collisional losses. An attempt to fit a collision-based model [13] showed significantly poorer agreement with the data.

The three rates R_1, R_2, and R_3 were extracted from the measurements by conducting a least-squares fit of a numerical solution to Eq. (1) to the measured fluorescence data, assuming the fluorescence intensity was proportional to N_{MOT}. Five parameters were varied in the fitting procedure: the initial reservoir population $N_{\mathrm{RES}}(0)$ (which also served as a scale factor), the product $f_{\mathrm{ex}} R_1$, and the three rates R_2, R_3, and R_{load}. An example of the fitting result is shown with a solid line in Fig. 2, where excellent agreement between model and experiment is seen.

The extracted product $f_{\mathrm{ex}} R_1$ is plotted in Fig. 3 as a function of MOT power and detuning. In order to isolate the value of R_1, a fit to the measured values of $f_{\mathrm{ex}} R_1$ was carried out using the expected saturation behavior of f_{ex} as a function of power and detuning [1]. Varying the detuning by adjusting the detector position in the laser locking

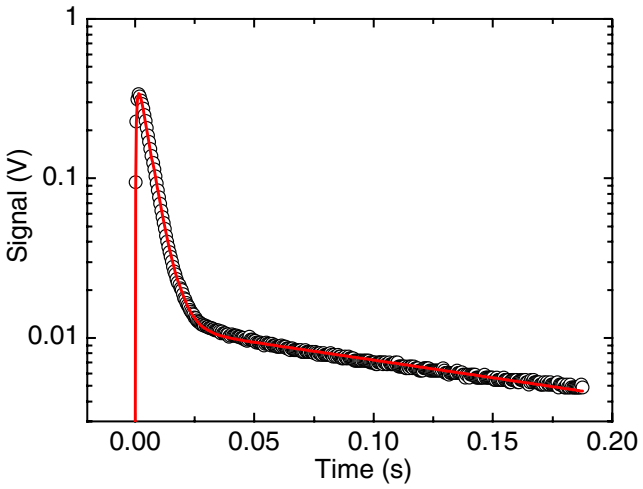

FIG. 2 (color online). Typical time dependence of the MOT fluorescence, beginning when the MOT light is turned on after both the slower and MOT beams have been off for 0.2 s. A clear two-component exponential decay is observed. Experimental values are indicated by open circles, and a fit of the model of Eq. (1) is indicated by a solid line (red online).

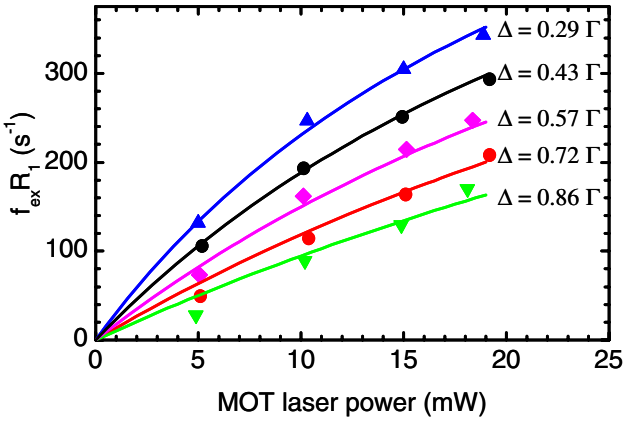

FIG. 3 (color online). Values of $f_{ex}R_1$ extracted from the model fit vs MOT power for five different detunings. Symbols indicate experimental values, with uncertainties about the size of the plotting symbols. Solid lines indicate a fit of Eq. (2) to the data. Note that Eq. (2) was fit simultaneously to all detunings and intensities to yield a single set of parameters R_1, a_1, and a_2.

scheme [10], we used the fitting function

$$F(P_{\mathrm{MOT}}, d) = \frac{a_1 P_{\mathrm{MOT}}}{2 + 2a_1 P_{\mathrm{MOT}} + a_2 d^2} R_1 \qquad (2)$$

where P_{MOT} is a measure of the MOT power, a_1 relates P_{MOT} to the saturation parameter I/I_{sat}, d is the detector position in mm (proportional to the detuning), and a_2 relates d to the detuning in units of the natural transition rate Γ. The three parameters R_1, a_1, and a_2 were allowed to vary in the least-squares fitting process, and the curves associated with the optimum values $R_1 = (1695 \pm 43)\ \mathrm{s}^{-1}$, $a_1 = (0.050 \pm 0.006)\ \mathrm{mW}^{-1}$, and $a_2 = (4.11 \pm 0.09)\ \mathrm{mm}^{-2}$ are shown in Fig. 3. We note that the values of a_1 and a_2 obtained from the fit are consistent with our knowledge of the natural linewidth [7] (and hence the saturation intensity), and an estimate of the locker calibration factor. The excellent agreement between model and experiment seen in Fig. 3 shows that the product $f_{ex}R_1$ scales simply with f_{ex}, and that a single composite loss rate R_1 provides an adequate description of the transfer of population to the metastable states. It is worth noting that R_1 is about 10 times smaller than the rough estimate discussed in Ref. [2], but this is not too surprising given the difficulty of estimating these transition rates. The rates R_2 and R_3, which essentially did not vary from run to run outside experimental uncertainty, were determined to be $(4.5 \pm 0.3)\ \mathrm{s}^{-1}$ and $(4.4 \pm 0.3)\ \mathrm{s}^{-1}$, respectively. The uncertainties in these values represent one-standard deviation of the average value over all 20 runs, derived from the random variation from run to run. The fact that these two rates are very similar in magnitude is interesting, but probably coincidental. The extracted load rate R_{load} varied from 900 to 1900 s^{-1}, depending on the detuning and intensity, as expected.

In conclusion, we have observed a robust magneto-optical trap for the first time in an atom with extensive potential for optical-pumping losses. We have explained the surprisingly high atom population by invoking a recycling mechanism based on magnetostatic trapping of high-J metastable states, a simple model of which agrees well with a series of measurements of MOT population time dependence. The demonstration of such a magneto-optical trap opens a range of possibilities for trapping and cooling of rare earths, as well as other open-shell atoms in the periodic table, greatly expanding opportunities for practical applications and fundamental studies using laser-cooled atoms.

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[1] H. J. Metcalf and P. van der Straten, *Laser Cooling and Trapping* (Springer, New York, 1999).
[2] H. Y. Ban, M. Jacka, J. L. Hanssen, J. Reader, and J. J. McClelland, Opt. Express **13**, 3185 (2005).
[3] L. Santos, G. V. Shlyapnikov, P. Zoller, and M. Lewenstein, Phys. Rev. Lett. **85**, 1791 (2000).
[4] S. B. Hill and J. J. McClelland, Appl. Phys. Lett. **82**, 3128 (2003).
[5] Data obtained from W. C. Martin, R. Zalubas, and L. Hagan, *Atomic Energy Levels - The Rare Earth Elements*, NBS, National Standards Reference Data Series—60 (U.S. GPO, Washington, DC, 1978). Data also available online at http://physics.nist.gov/PhysRefData/Handbook/index.html.
[6] E. L. Raab, M. Prentiss, A. Cable, S. Chu, and D. E. Pritchard, Phys. Rev. Lett. **59**, 2631 (1987).
[7] While analyzing the results described in this Letter, it became clear to us that the accepted value of 5.8 ns for the lifetime of this transition (cf. http://physics.nist.gov/PhysRefData/Handbook/index.html) was not consistent with our observations. As a result, we carried out a crossed-beam laser-induced-fluorescence measurement of the natural linewidth and found it to be (35.6 ± 1.2) MHz, corresponding to a lifetime of 4.5 ns. Details of this measurement will be presented in a future publication.
[8] Unless otherwise noted, all uncertainty estimates in this Letter are intended to be interpreted as one-standard deviation combined standard uncertainty.
[9] T. E. Barrett, S. W. Dapore-Schwartz, M. D. Ray, and G. P. Lafyatis, Phys. Rev. Lett. **67**, 3483 (1991).
[10] J. J. McClelland and M. H. Kelley, Phys. Rev. A **31**, 3704 (1985).
[11] C. C. Bradley, J. J. McClelland, W. R. Anderson, and R. J. Celotta, Phys. Rev. A **61**, 053407 (2000).
[12] T. P. Dinneen, C. D. Wallace, K.-Y. N. Tan, and P. L. Gould, Opt. Lett. **17**, 1706 (1992).
[13] M. G. Prentiss, A. Cable, J. E. Bjorkholm, S. Chu, E. L. Raab, and D. E. Pritchard, Opt. Lett. **13**, 452 (1988).