Investigation of sub-Doppler cooling in an ytterbium magneto-optical trap

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(Received 20 March 2003; published 25 July 2003)

We report experimental evidence of Sisyphus cooling in atoms with a $^1S_0$ ground state. Since $J=0$, any cooling mechanism which requires multiple sublevels can only occur in the isotopes which have nuclear spin $I\neq 0$. Ytterbium has seven stable isotopes and offers a unique system in which we can study cooling on $F=0\rightarrow 1$ (^{168,170,172,174,176}Yb), $F=1/2\rightarrow 3/2$ (^{171}Yb), and $F=5/2\rightarrow 7/2$ (^{173}Yb), depending on the selection of isotope. We have trapped each of the seven stable isotopes of ytterbium in a magneto-optical trap (MOT) using the strong $^1S_0$-$^1P_1$ transition, and transferred them into a second MOT which uses the much narrower $^1S_0$-$^3P_1$ intercombination transition. We have measured the temperature of isotopes ^{171}Yb, ^{173}Yb, and ^{174}Yb in the $^1S_0$-$^3P_1$ MOT, as a function of the intensity and detuning of the trapping laser. The temperature of ^{174}Yb was found to increase more rapidly with intensity than predicted by Doppler cooling theory, in agreement with earlier work on alkaline-earth atoms. In the odd isotopes the temperature was found to decrease with increasing angular momentum, as observed in earlier experiments and three-dimensional simulations.

DOI: 10.1103/PhysRevA.68.011403 PACS number(s): 32.80.Pj, 32.80.Lg, 42.50.Vk, 42.60.By

Optical molasses [1] and magneto-optical traps (MOT) [2] are widely used for producing and studying cold samples of dilute gases of neutral atoms, and these techniques serve as a starting point for many experiments. However, details of the cooling process are still unexplored and deserve closer attention. Group II atoms offer an interesting alternative to alkali-metal atoms [3–5] for investigating both Doppler and sub-Doppler cooling mechanisms. Group II atoms have two electrons in the valence shell, resulting in zero electronic angular momentum in the ground state. The even isotopes have no nuclear spin ($I=0$) and Doppler cooling can be studied without the effects of sub-Doppler Sisyphus cooling which dominate when there are multiple levels in the ground state. On the other hand, odd isotopes have multiple ground-state levels due to their nonzero nuclear spin and one can study Sisyphus cooling as a function of ground-state spin in different isotopes.

Our present work on ytterbium (Yb, $Z=70$) is an experimental study of sub-Doppler cooling in atoms with no electron angular momentum in the ground state [19]. Doppler cooling and sub-Doppler cooling are studied on one element, so they can be directly compared under the same conditions by simply switching isotopes. Yb has the advantage that it has several stable isotopes with high natural abundances: five even isotopes with $I=0$ (^{168,170,172,174,176}Yb) and two odd isotopes, ^{171}Yb with $I=1/2$ and ^{173}Yb with $I=5/2$ (see Fig. 1).

In the even isotopes, which should experience pure Doppler cooling, we observe a more rapid increase of the atom temperature with laser intensity than predicted by Doppler cooling theory, in agreement with earlier results published for ^{40}Ca [6] and ^{88}Sr [7]. Compared to the even isotopes, we observe significantly colder temperatures in the odd isotopes of Yb, as expected from the effects of Sisyphus cooling when $I\neq 0$. Having two odd isotopes with different spins allows us to compare the results with only a slight change in the laser tuning.

In this paper, we present a comparison of laser cooling in three isotopes of Yb in a $^1S_0$-$^3P_1$ MOT: ^{174}Yb ($F_g=0\rightarrow F_e=1$), ^{171}Yb ($F_g=1/2\rightarrow F_e=3/2$), and ^{173}Yb ($F_g=5/2\rightarrow F_e=7/2$). The intercombination $^1S_0$-$^3P_1$ green line used for these data has two advantages over the stronger $^1S_0$-$^1P_1$ blue line (see Fig. 1). It has a longer lifetime of 850 ns, leading to a lower Doppler temperature limit of 4.4 μK, and it is a completely closed transition, so the trap lifetime is limited only by Yb-Yb and background gas collisions. With a typical pressure in the 10^{-12} Torr range in our ultrahigh vacuum system, we have observed trap lifetimes of about 75 s for the $^1S_0$-$^3P_1$ transition, longer by a factor of 25 than the previously published lifetime [8], presumably due to our better vacuum. The $^1S_0$-$^1P_1$ trap lifetime is limited to ~800 ms by the decay branching ratio of $^1P_1$ state into the D states [9].

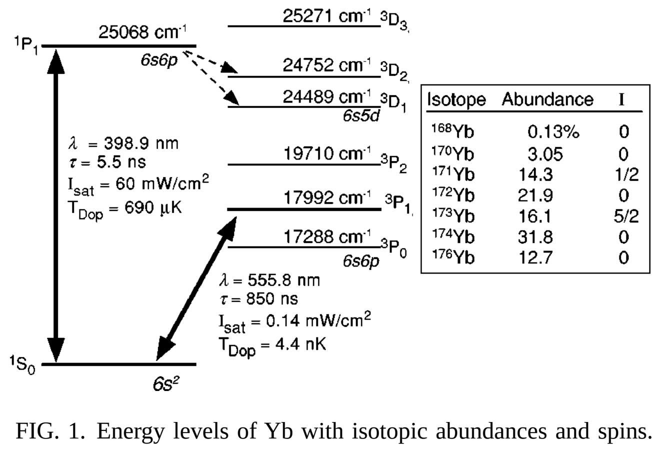

FIG. 1. Energy levels of Yb with isotopic abundances and spins.

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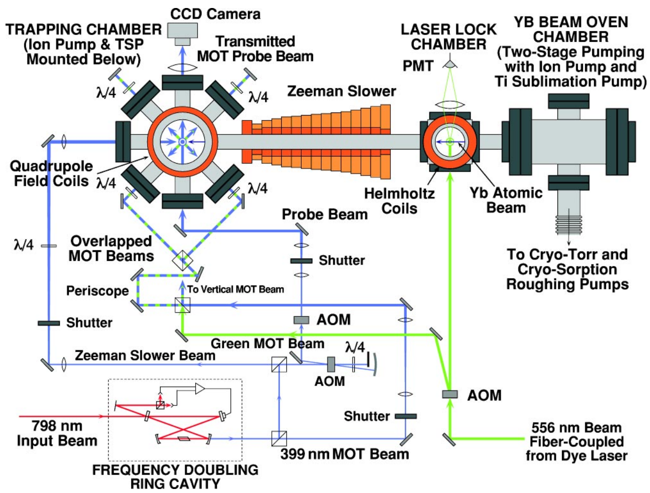

FIG. 2. Diagram of the Yb MOT apparatus.

Our Yb MOT is of the standard three-axis retroreflected configuration loaded from an atomic beam (see Fig. 2). The beams parallel to the axis of the quadrupole coils are twice as intense as the beams orthogonal to it. We use the stronger $^1S_0$-$^1P_1$ transition at 399 nm for Zeeman slowing and the initial cooling and trapping. The laser at 399 nm is produced by doubling the frequency of the output from a Titanium:sapphire laser (Coherent 899-21) with an LBO (lithium triborate) crystal in an external cavity in bowtie configuration [10,11]. The Zeeman slower is of the decreasing magnetic-field configuration and is offset by a bias field to allow for a laser detuning of 325 MHz below resonance, via a double pass through an acousto-optic modulator (AOM), to avoid pushing the atoms out of the trap. With 8 mW in the Zeeman slower and 70 mW of total laser power in the trap beams at 399 nm, we typically trap a cloud of 10^6 atoms of ^{174}Yb, roughly 2 mm in size, with a lifetime as long as 800 ms depending on various conditions such as laser intensity and detuning.

The green light at 556 nm is produced with a ring dye laser (Coherent 899-21). To take advantage of the narrow 190 kHz linewidth of the $^1S_0$-$^3P_1$ transition, we use the Pound-Drever-Hall method [12] to narrow the laser to $<$200 kHz, by locking the laser to an external cavity. The external cavity is locked with adjustable detuning to the desired transition of Yb, using the atomic beam before it enters the Zeeman slower. A circularly polarized 556-nm laser beam intersects the atomic beam at 90° and is retroreflected. An error signal for locking to the center of the Yb line is produced by modulating a magnetic field which is applied parallel to the laser beam. The fluorescence signal is monitored with a photomultiplier tube (PMT), demodulated by a lock-in detector, and fed back to the external cavity. The overall detuning is controlled by changing the magnetic-field bias.

The green and blue trapping laser beams are combined at a beam splitter cube and the overlapping beams copropagate through the MOT. The green trapping beams are left on during the initial cooling and trapping with the stronger blue transition. The atoms are transferred into the green intercombination MOT with ~70% efficiency by simply turning off the blue beams abruptly with a mechanical shutter.

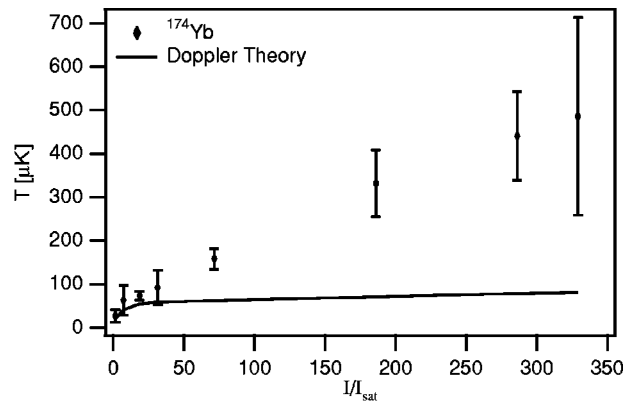

FIG. 3. Trap temperature vs normalized trap-laser intensity, I/I_{sat}, at a detuning $\Delta = 13\Gamma$ in ^{174}Yb. The solid line shows the temperature calculated from Doppler cooling theory, including the displacement in position of the clouds due to gravity. The error bars are the standard deviation of the mean of 2–10 measurements at a given intensity.

Two absorption images are taken to determine the temperature of the clouds of trapped atoms with a time-of-flight (TOF) method, one while the trap is still on and one after the trap is turned off and the clouds are allowed to expand for a prescribed time. The timing is controlled by a pulse generator (PulseBlaster from SpinCore Technologies) in the following sequence: after the transfer from the blue to the green MOT, we wait for 100 ms to let the atoms come to an equilibrium. Then the green laser intensity, frequency, and magnetic field gradient are gradually changed over 100 ms to bring the MOT to the condition of interest. After the atoms are allowed to settle again over 100 ms, the first image is taken. The probe beam used for the absorption imaging is on resonance with the $^1S_0$-$^1P_1$ transition and has a 1 cm diameter, power of 0.1 mW and 50 μs duration. We have verified that no detectable number of atoms is lost during this first imaging. The atoms are again allowed to settle over 350 ms (limited by the refresh rate of the camera), then the green laser is turned off with an AOM and another image is taken after the cloud expands for a specified TOF of 3–10 ms. The temperature is determined by comparing the root-mean-square widths extracted by fitting a two-dimensional (2D) Gaussian spatial distribution to the cloud images before and after expansion. The temperature is then $T = M\langle v_{rms}^2\rangle / k_B$, where $\langle v_{rms}^2\rangle = (\langle x_f^2\rangle - \langle x_i^2\rangle)/\tau_{TOF}^2$ is the mean-square velocity of the atoms, x_i and x_f are the initial and final widths, respectively, extracted from the fit, and τ_{TOF} is the time that the cloud is allowed to expand.

Figure 3 shows the temperature measured for ^{174}Yb as a function of the trap-laser intensity. As mentioned earlier, the even isotopes of Yb have no sublevels in the ground state and it is possible to explore the effects of Doppler cooling independent of the dominating effects of sub-Doppler cooling. The temperature expected from Doppler cooling theory is

$$T = \frac{\hbar\Gamma}{8k_B}\frac{\Gamma}{\Delta}\left(1 + \frac{I}{I_{sat}} + 4\frac{\Delta^2}{\Gamma^2}\right), \tag{1}$$

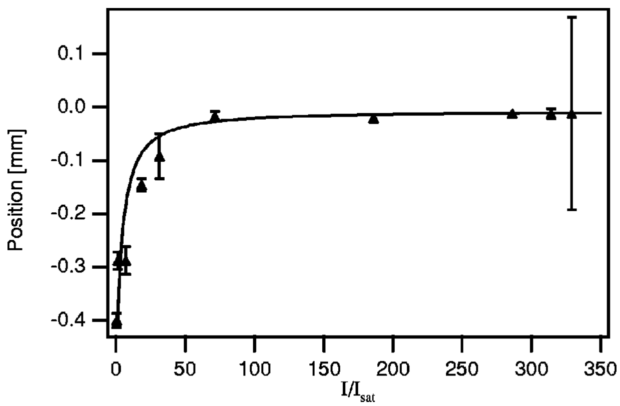

FIG. 4. Vertical position of the cloud of ^{174}Yb as a function of trap beam intensity. The triangles are the measured positions of the trapped atom cloud and the solid line shows the calculated position as a function of light intensity, which would balance the forces of light and gravity for the given detuning ($\Delta = 13\Gamma$) and magnetic-field gradient ($\partial B/\partial z = 16.5$ G).

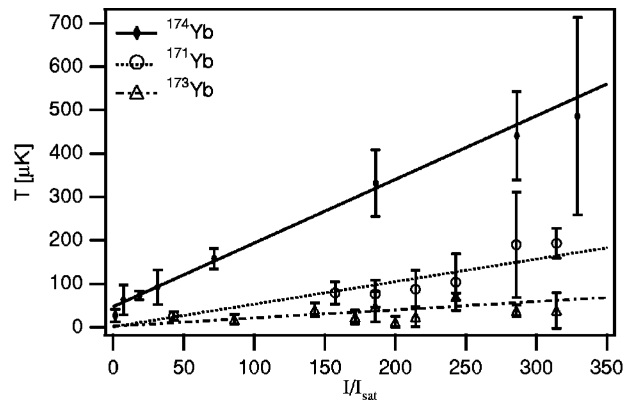

FIG. 5. Temperature vs I/I_{sat} at $\Delta = 13\Gamma$ in ^{174}Yb, ^{171}Yb, and ^{173}Yb. The filled diamonds and solid line are the measured temperature of ^{174}Yb and its linear fit, empty circles are for ^{171}Yb, and filled triangles are for ^{173}Yb.

where $\Gamma = 1/\tau$ is the natural linewidth of the transition, Δ is the detuning of the laser, I is the total intensity of the trapping lasers, and $I_{sat} = \pi hc\Gamma/(3\lambda^3)$ is the saturation intensity [4]. As expected, we observe a linear dependence of temperature on intensity except at the lowest intensities where the effects of gravity change the equilibrium position of the atoms. The effect of gravity is included in the theoretical curve shown in Fig. 3.

The temperature, however, increases much more rapidly than expected from Eq. (1). For the detuning shown here, the temperature of ^{174}Yb rises roughly 17 times more rapidly than predicted by the Doppler theory. The data presented for the temperature of ^{88}Sr in Ref. [7], obtained in a σ^+-σ^- MOT configuration for the $^1S_0$-$^1P_1$ transition, rises at a similarly rapid rate of 14 times that of Eq. (1). The cause for the rapid rise in temperature is not yet known.

At low intensities, we have found that the temperature does not have a linear dependence on the intensity due to the influence of gravity. The vertical position of the atom cloud moves downward with decreasing light intensity (see Fig. 4). Because the intercombination line is relatively weak, the force of gravity on the atoms is comparable to that of the trap beams at lower intensities and at the laser detuning used here, $\Delta = 13\Gamma$, chosen for optimal transfer from the blue MOT into the green MOT. Thus, the atoms drop in position until the magnetic-field gradient of the MOT brings the effective detuning of the upward beam closer to resonance, increasing the upward force from the trapping beams. As shown in Fig. 4, the observed vertical positions agree with the calculated equilibrium positions. According to Doppler cooling theory, the reduced detuning of the upward beam should lower the temperature of the trapped atoms and the data in Fig. 3 begin to show this downward trend at the lowest intensities.

Figure 5 shows the temperature measured for the odd isotopes ^{171}Yb and ^{173}Yb, as a function of intensity. The data for ^{174}Yb from Fig. 3 are included for comparison. The odd isotopes are colder than ^{174}Yb, since Sisyphus cooling takes place in these isotopes due to the nonzero nuclear spin. Also, Sisyphus cooling should produce a lower temperature in the isotope with the larger nuclear spin, in agreement with the data.

The temperature for the orthogonal linear polarization configuration (lin $\perp$ lin) in three dimensions was calculated for $J_g \rightarrow J_e = J_g + 1$ systems, for $J_g = 1,2,3,4$ in Ref. [13]. It was shown that for $|\Delta| \gg \Gamma$, the temperature changes linearly with intensity, for $I \gg I_{sat}$,

$$3k_BT/2 \simeq a\hbar|\Delta|s/2 + b, \tag{2}$$

where $s = (I/I_{sat})[1 + (2\Delta/\Gamma)^2]^{-1}$, b is an offset, and slope a depends only on J_g and is independent of the mass, transition wavelength, or the detuning. It was shown in Ref. [14] that the localization of atoms in regions with higher laser intensity must be taken into account to correctly predict the temperature of atoms in molasses in a lin $\perp$ lin configuration. Although the 3D lin $\perp$ lin and σ^+-σ^- configurations have markedly different polarization patterns, the average degree of Sisyphus coupling (averaged over relative phases of the orthogonal beams) has been shown to be within a few percent, for the two configurations [15]. Also, it has been shown experimentally that both configurations have strong 3D localization effects for arbitrary relative phases among the beams, and the influence of the phase variation is small [16]. The slopes calculated in Ref. [13] were in good agreement with experimental results from ^{87}Rb and ^{85}Rb ($J_g = 2$ and 3, respectively) [14] and ^{133}Cs ($J_g = 4$) [17]. In our case, the angular momentum of the ^{173}Yb isotope falls in the range covered by the calculation. Our result for this isotope in the MOT σ^+-σ^- configuration agrees within error bars with what was predicted for the lin $\perp$ lin configuration. However, our slope is also consistent with the detailed modeling and measurements of a Rb MOT, in which the slope was found to be 30% higher than for the lin $\perp$ lin configuration [18]. Table I summarizes these results. The errors are the standard deviation of the mean of repeated measurements. The atoms are trapped in a cloud with radius of roughly 0.15 mm, which translates to a maximum Zeeman shift of 3Γ in the magnetic-field gradient of the MOT. This makes the uncer-

TABLE I. Dimensionless slope a, as defined in text, giving the temperature vs laser intensity normalized for detuning and transition linewidth for polarization gradient cooling. The errors are the standard deviation of the mean of repeated measurements. All entries are for lin$\perp$ lin configuration except for those from our work, which are in $\sigma^+ - \sigma^-$ MOT configuration.

J_g	a (calculated) [a]	a (measured)
1/2	...	9.0 $\pm$ 1.7 (this work)
1	3.3 $\pm$ 0.5	...
2	2.6 $\pm$ 0.2	2.3 $\pm$ 0.2 [b]
5/2	...	3.3 $\pm$ 1.2 (this work)
3	2.5 $\pm$ 0.2	2.1 $\pm$ 0.2 [b]
4	2.1 $\pm$ 0.2	2.1 $\pm$ 0.5 [c]

[a]See Ref. [13].
[b]See Ref. [14].
[c]See Ref. [17].

tainty in a due to Zeeman shift by the MOT field small compared to the quoted errors.

In conclusion, we have measured the temperature of three isotopes of ytterbium, ^{174}Yb ($I=0$), ^{171}Yb ($I=1/2$), and ^{173}Yb ($I=5/2$), in a MOT. We have found that an isotope which offers a two-level cooling system, ^{174}Yb, has a significantly higher slope of temperature versus intensity than predicted by Doppler cooling theory, in good agreement with previous results in Sr. Sisyphus cooling in the odd isotopes due to their additional sublevels in the ground state from the nuclear spin has been observed and results in significantly lower temperatures. We found that the temperature as a function of normalized intensity decreases with higher angular momentum in the ground state, and the dependence was found to be similar to values predicted by 3D simulations and measurements in alkali metals for lin$\perp$ lin configuration cooling. In the future, to obtain a more direct comparison with Sisyphus modeling, these temperature measurements could be made in optical molasses, thereby enabling the use of the lin$\perp$ lin configuration of beams and eliminating the detuning effects of the MOT magnetic field. ^{171}Yb is an interesting case because spin-1/2 is the lowest angular momentum that can have Sisyphus cooling, and has no effects of corkscrew cooling [3]. Thus, all sub-Doppler cooling could be eliminated by controlling the relative phases of the molasses beams in σ^+-σ^- configuration.

The authors would like to thank Jean Dalibard and Klaus Mølmer for helpful discussions, and Warren Nagourney for invaluable advice on the lasers. Thanks also to Clark Griffith, Claire Cramer, David Norris, and Courtney Taylor for their assistance with the apparatus development. This work was supported by National Science Foundation Grant No. PHY-0099535.

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