Laser cooling and trapping of Yb from a thermal source

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Abstract

We have successfully loaded a magneto-optic trap for Yb atoms from a thermal source without the use of a Zeeman slower. The source is placed close to the trapping region so that it provides a large flux of atoms that can be cooled and captured. The atoms are cooled on the $^1S_0 \leftrightarrow ^1P_1$ transition at 398.8 nm. We have loaded all seven stable isotopes of Yb into the trap. For the most abundant isotope ($^{174}$Yb), we load more than $10^7$ atoms into the trap within 1 s. For the rarest isotope ($^{168}$Yb) with a natural abundance of only 0.13%, we still load about $4 \times 10^5$ atoms into the trap. We find that the trap population is maximized near a detuning of $-1.5\Gamma$ and field gradient of 75 G/cm.

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1. Introduction

Laser-cooled atoms open exciting new possibilities for several experiments including those in precision spectroscopy. Yb is a particularly good choice for such studies because of several reasons. Yb has been proposed for experiments in quantum optics$^{1,2}$ due to the existence of two nearly-closed low-lying excited states with widely differing lifetimes. Laser-cooled Yb has been proposed for optical frequency standards applications$^3$. Yb has been shown to be a

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useful candidate for the test of electroweak interactions because there is an enhanced parity-violation effect in the $^1S_0 \leftrightarrow ^3D_1$ transition. Laser-cooled Yb extends the possibilities in measuring the strength of parity-violating interactions with unprecedented accuracy due to the availability of dense samples where one can apply large electric fields and homogeneous magnetic fields. Furthermore, Yb has a wide range of stable isotopes, both fermionic and bosonic, allowing one to explore the possibility of studying the properties of fermion-boson mixtures.

The starting point of most laser-cooling experiments is the magneto-optic trap (MOT). The source of atoms for the MOT is usually an oven inside the vacuum chamber containing a small amount of pure metal which is heated to release a beam of atoms. For atoms with high melting point such as Na, the hot atoms emanating from the oven are first slowed by a counter-propagating laser beam (Zeeman slower or chirp slower). Yb has a melting point of 819°C and previous experiments have used a Zeeman slower for loading the MOT. However, we have earlier shown that a MOT for Rb atoms can be loaded efficiently from a thermal getter source operating at temperatures near 300°C without the use of a slower. Since Yb has considerable vapor pressure over the solid at 300°C, we have been exploring the possibility of loading a Yb MOT directly from a thermal source.

In this paper, we show that this is indeed possible by successfully loading all the seven stable isotopes of Yb into the MOT from a thermal source. For the most abundant isotope ($^{174}$Yb), we load about $1.7 \times 10^7$ atoms with a time constant of 190 ms. Most significantly, we can trap the rarest isotope ($^{168}$Yb) which has a natural abundance of only 0.13%. There are two factors that make this possible. The first is that the oven is placed close to the trapping region so that it provides a large flux of atoms that can be captured by the MOT. The second factor is that the excited state lifetime of the cooling transition is only 5.68 ns and the photon scattering rate is very high. Atoms are slowed over a short distance and small laser beams of 10 mm diameter are enough to cool and capture atoms from the background vapor.
2. Experimental details

Yb has two possible cooling transitions, as seen from the energy level diagram in Fig. 1. The $^1S_0 \leftrightarrow ^3P_1$ intercombination line at 555.8 nm forms a pure two-level system in Yb due to the absence of ground-state hyperfine structure. The transition has a long lifetime of 874 ns corresponding to a natural linewidth of $\Gamma = 2\pi \times 182 \text{ kHz}$, and therefore the photon cycling rate is very slow. However, the Doppler cooling limit is 4 $\mu$K, a very desirable temperature for high-precision measurements. The other cooling transition is the $^1S_0 \leftrightarrow ^1P_1$ transition at 398.9 nm. This has a short lifetime of 5.68 ns or a linewidth of $\Gamma = 2\pi \times 28 \text{ MHz}$, and allows photons to be cycled quickly. However, it has the disadvantage of giving a high Doppler cooling limit of 670 $\mu$K, and is not a completely closed transition since the excited state can branch into the low-lying $^3P$ levels through the intermediate $^3D$ levels. Despite these disadvantages, we have decided to use the 398.9 nm transition for our experiments primarily because the high photon scattering rate allows atoms to be cooled over a short distance.

The laser light for the 398.9 nm transition is produced in a two-step process. First, the output of a tunable Ti-sapphire laser (Coherent 899-21) is set to half the desired frequency near 798 nm. Then its output is fed into an external-cavity frequency-doubling unit (Laser Analytical Systems, LAS100) which uses a nonlinear crystal of lithium triborate to produce the desired 398.8 nm light. The Ti-sapphire laser is actively stabilized using an ovenized, Fabry-Perot reference cavity and its instantaneous linewidth is less than 1 MHz. We have also measured that its long-term drift is only a few MHz per hour, which makes it unnecessary to lock the laser to an external reference. For our experiments, we find that it is sufficient to set the frequency at the desired point and leave it for the duration of the experiment. The frequency is set using a home-built wavemeter\textsuperscript{11} that uses a scanning Michelson interferometer and a Rb-stabilized reference laser. The wavemeter has an absolute accuracy of a few MHz which is more than sufficient for finding the Yb lines. Once the trap is working, the trap fluorescence signal is used to optimize the laser frequency or detuning.

The experiments are done inside a vacuum chamber consisting of a standard six-way cross
made of pyrex with 25-mm O.D. windows. The pyrex cell is pumped by a 20 l/s ion pump and maintained at a pressure below $10^{-9}$ torr. The source of Yb atoms is a quartz ampoule containing a small amount of elemental Yb. The ampoule is a 30 mm long tube of 5 mm diameter that is sealed at one end and constricted to 1 mm diameter at the other end. The constriction seems important both in ensuring a uniform flux in the trapping volume and in preventing the walls from getting coated with a film of Yb. Using a collimated thermal beam, as is the case when using a Zeeman slower, causes the opposite wall to get rapidly coated with a thick film of Yb. On the other hand, we find no such deposit even after 50 hours of operation of the source. The source is placed about 50 mm from the trap center. It is resistively heated to a temperature of 300–400°C to release Yb.

The MOT is formed from a standard configuration consisting of three pairs of mutually orthogonal laser beams and a quadrupole magnetic field superposed at the intersection of the beams. The total laser power available near the MOT is 90 mW. This is split into three circularly-polarized beams. Each beam has a power of 30 mW and diameter of 10 mm. The saturation intensity $I_0$ for the transition is 58 mW/cm$^2$, therefore the intensity in the beams is about $0.65I_0$. The beams are retroreflected after passing through the cell, and the intensity in the return beams is slightly smaller due to losses along the optical path. The quadrupole magnetic field is produced using a pair of coils (270 turns each) placed 40 mm apart. With 3 A of current through the coils, the field gradient at the center is 90 G/cm. There is negligible heat generation in the coils at this current. The fluorescence from the trapped atoms is imaged on to a calibrated photo-multiplier tube (PMT). The number of trapped atoms is estimated from the total power incident on the PMT after accounting for losses along the optical path$^{10}$. There is an error of about 20% in estimating the number of atoms in this manner, but relative values between isotopes and other such trends are unaffected by this error.
3. Results and discussion

In the first set of experiments, we scanned the laser slowly across a frequency range of 3 GHz. The fluorescence signal detected by the PMT is shown in Fig. 2. The signal shows peaks as each isotope comes into resonance and gets trapped in the MOT. The peak heights correspond roughly to the natural abundance of each isotope except for the odd isotopes which show anomalous behavior. This is because the odd isotopes have half-integer nuclear spin and consequently have hyperfine structure in the $^1P_1$ excited state. In these cases, optical pumping into the wrong hyperfine level causes additional loss from the trap. The signal from the rarest isotope $^{168}$Yb is also seen in the figure. As shown in the inset of Fig. 2, the $^{168}$Yb peak becomes clearer when the gain of the PMT is increased by a factor of 100.

In order to better characterize the source and find optimal values for the laser detuning, we have studied the trap population as a function of laser frequency. The laser was scanned slowly over a frequency range of 100 MHz below the resonance. The results for $^{174}$Yb are shown in Fig. 3. The number of trapped atoms shows a peak value of $1.7 \times 10^7$ at a detuning of $-1.5 \Gamma$. This is similar to the behavior seen in the case of a Rb MOT loaded from a thermal source$^{10}$. Note that the optimal value of detuning depends on the size of the trapping beams and the magnetic-field gradient, since both these parameters are important in determining the distance over which atoms are slowed and captured. The data in Fig. 3 were taken with a magnetic field gradient of 75 G/cm. All the other isotopes show similar dependence on detuning.

The loading of the MOT from a thermal source follows a rate equation$^{10}$

$$\frac{dN}{dt} = R - \frac{N}{\tau},$$

where $N$ is the number of atoms in the trap, $R$ is the rate at which atoms are captured from the source, and $\tau$ represents the losses from the trap. In the case of Yb, there are several factors that contribute to the loss rate. The dominant mechanism is collisional losses, both due to collisions with background atoms and collisions with hot, untrapped Yb atoms. In
addition, as mentioned before, the $^1P_1$ excited state of the cooling transition can branch into the low-lying $^3P$ levels. Of these, the $^3P_0$ and $^3P_2$ levels are metastable levels; atoms shelved into these levels no longer participate in the cooling cycle and are rapidly lost from the trap$^9$.

We have studied the loss mechanisms in the trap by studying the loading characteristics of the MOT for the different isotopes. The solution to the rate equation in Eq. 1 is an exponential growth in the number of trapped atoms: $N = N_s[1 - \exp(-t/\tau)]$, where $N_s$ is the steady state population and is given by $R\tau$. The loading characteristics of the most abundant isotope $^{174}$Yb and the least abundant isotope $^{168}$Yb are shown in Fig. 4. Both curves follow the exponential behaviour predicted from Eq. 1. Deviation from the exponential curve would indicate other loss mechanisms. For example, losses due to collisions between trapped atoms would appear as an $N^2$ term in Eq. 1$^{12}$. Under our conditions, such intra-trap collisional loss does not seem significant. From Fig. 4, we see that for $^{174}$Yb the time constant is 190 ms and the steady state population is $1.3 \times 10^7$. For $^{168}$Yb, the time constant is 440 ms while the steady state population is about 40 times smaller. We should also mention that the optimal value of magnetic-field gradient for trapping $^{174}$Yb and $^{168}$Yb are different, with values of 75 G/cm and 60 G/cm, respectively.

The characteristics of the source and the loss mechanisms become more apparent by studying the values of $\tau$ and $N_s$ for the different isotopes under identical conditions. The measured values are listed in Table 1. The data were taken at a detuning of $-1.2\Gamma$ and field gradient of 75 G/cm. The value of $\tau$ for the different isotopes lies in that range of 160–450 ms, while $N_s$ varies from $3 \times 10^6$ to $1.3 \times 10^7$. The general trend is that $\tau$ decreases and $N_s$ increases with the natural abundance of the isotope, except for the odd isotopes which, as mentioned before, show anomalous behavior due to optical pumping in the excited-state hyperfine levels. The trends become clearer if we consider the values for the loading rate and $N_s$ for each isotope normalized to the corresponding value for $^{174}$Yb, as listed in Table 2. For the even isotopes, the loading rate scales as the natural abundance, as expected from a non-enriched source. On the other hand, the value of $N_s$ scales roughly as the square root...
of the natural abundance, implying that $\tau$ is inversely proportional to the square root of the abundance. One possible explanation for this is that the cross-section for collisions with same isotope atoms are larger than the cross-section for collisions with other isotopes.

4. Conclusions

We have successfully loaded a MOT for Yb atoms from a thermal source without the necessity of a Zeeman slower. The source is placed close to the trapping region so that it provides a large flux of atoms that can be captured by the MOT. We have loaded all seven stable isotopes of Yb. For the most abundant isotope ($^{174}$Yb), we load about $2 \times 10^7$ atoms into the trap within 1 s. Even for the rarest isotope ($^{168}$Yb) with a natural abundance of only 0.13%, we load about $4 \times 10^5$ atoms into the trap. We have studied the trap population as a function of laser detuning and find that the population is maximized near a detuning of $-1.5\Gamma$. We have characterized the losses from the trap by studying the loading of the MOT as a function of time. We find that the number of trapped atoms grows exponentially with a time constant that scales as the inverse square root of the natural abundance of the isotope. Trap losses due to optical pumping into the metastable $^3P_0$ and $^3P_2$ levels could be a significant limitation on the number of trapped atoms. In future, we plan to clear out these levels using diode lasers at 649 nm (exciting the $^3P_0 \rightarrow ^3S_1$ transition) and at 770 nm (exciting the $^3P_2 \rightarrow ^3S_1$ transition). With these improvements, we expect to get increased population and lifetime in the trap which is important for many of the proposed experiments using laser-cooled Yb.

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FIGURES

Fig. 1. Yb energy levels. The figure shows the relevant low-lying energy levels in Yb. Even-parity states are on the left and odd-parity states on the right. The two possible cooling transitions at 398.9 nm and 555.8 nm are shown.

Fig. 2. MOT fluorescence vs. laser frequency. The fluorescence signal shows peaks as each isotope comes into resonance with the laser and is trapped in the MOT. Each peak is labeled by the corresponding isotope number. The inset shows a 100× magnified view of the region where $^{168}$Yb is trapped.

Fig. 3. Number of trapped atoms vs. detuning. The number of $^{174}$Yb atoms in the MOT is shown as the detuning of the laser is varied slowly from $-60$ MHz ($-2\Gamma$) to 0. The magnetic field gradient at the trap center was 75 G/cm. The number of atoms shows a peak at $-42$ MHz or $-1.5\Gamma$. Other isotopes show identical behavior.

Fig. 4. Loading of the MOT. The build up of the number of atoms in the MOT is shown after the trapping beams are turned on at $t = 0$. In (a), we have a MOT for $^{174}$Yb at a detuning of $-1.2\Gamma$ and field gradient of 75 G/cm. In (b), we observe signal from a MOT for $^{168}$Yb at a detuning of $-1.2\Gamma$ and field gradient of 60 G/cm. Both curves show exponential growth in the number of atoms with time constants of 190 ms and 440 ms, respectively. Note that under steady state, the number of trapped $^{168}$Yb atoms is about 40 times smaller.
TABLES

Table 1. Listed are the loading time constant $\tau$ and steady state population $N_s$ in the MOT for the various isotopes. The data for each isotope were taken at a detuning of $-1.2\Gamma$ and field gradient of 75 G/cm. The errors in $\tau$ are statistical $1\sigma$ deviations. For $N_s$, there is a calibration error of about 20% due to errors in converting the detected fluorescence signal to the number of atoms. However, the error is the same for all isotopes and does not affect relative values.

| Isotope | Nat. abund. | $N_s$  | $\tau$ (ms) |
|---------|-------------|-------|------------|
| 176     | 12.7%       | $8.0 \times 10^6$ | 300(30)    |
| 174     | 31.8%       | $1.3 \times 10^7$ | 190(10)    |
| 172     | 21.9%       | $1.1 \times 10^7$ | 260(20)    |
| 173     | 16.1%       | $1.7 \times 10^6$ | 440(25)    |
| 171     | 14.3%       | $3.4 \times 10^6$ | 165(10)    |
| 170     | 3.05%       | $3.0 \times 10^6$ | 450(30)    |
Table 2. Listed are the loading rate $R$ and steady state population $N_s$ for the various isotopes from Table 1, normalized to the values for $^{174}\text{Yb}$. For the even isotopes, the loading rate scales as the isotopic abundance, as expected for a non-enriched thermal source. $N_s$ scales roughly as the square root of the abundance. The odd isotopes show different behavior due to excited-state hyperfine structure, as explained in the text.

| Isotope | Rel. abund. | $R/R^{174}$ | $N_s/N_s^{174}$ |
|---------|-------------|-------------|-----------------|
| $^{176}$ | 0.40        | 0.39(4)     | 0.62            |
| $^{174}$ | 1.00        | 1.00        | 1.00            |
| $^{172}$ | 0.69        | 0.61(5)     | 0.85            |
| $^{173}$ | 0.51        | 0.055(4)    | 0.13            |
| $^{171}$ | 0.45        | 0.30(2)     | 0.26            |
| $^{170}$ | 0.096       | 0.096(8)    | 0.23            |
