Atomic fountain of laser-cooled Yb atoms for precision measurements

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We demonstrate launching of laser-cooled Yb atoms in a cold atomic fountain. Atoms in a collimated thermal beam are first cooled and captured in a magneto-optic trap (MOT) operating on the strongly-allowed $^1S_0 \rightarrow ^1P_1$ transition at 399 nm (blue line). They are then transferred to a MOT on the weakly-allowed $^1S_0 \rightarrow ^3P_1$ transition at 556 nm (green line). Cold atoms from the green MOT are launched against gravity at a velocity of around 2.5 m/s using a pair of green beams. We trap more than $10^7$ atoms in the blue MOT and transfer up to 70% into the green MOT. The temperature for the odd isotope, $^{171}$Yb, is $\sim 1$ mK in the blue MOT, and reduces by a factor of 40 in the green MOT.

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I. INTRODUCTION

Laser cooling and trapping of Yb is different from the more common alkali-metal atoms because of its spin-zero ground state. It has two cooling transitions (one strong and one weak) with widely-differing Doppler temperature limits, and does not require the use of a re-pumping laser. In addition, it has 7 stable isotopes, of which 5 are bosonic and 2 are fermionic. This allows the comparative study of Fermi-Bose gas mixtures, particularly under conditions of quantum degeneracy. Furthermore, spin-exchange collisions in the closed-shell ground state are smaller compared to the alkali-metal atoms. This makes laser-cooled Yb an attractive candidate for precision measurements and atomic clocks.

One of us (VN) has recently proposed using laser-cooled Yb atoms launched in an atomic fountain for a high-precision test of the existence of a permanent electric dipole moment (EDM). The existence of an atomic EDM would be direct evidence of time-reversal symmetry violation in the laws of physics. Therefore, EDM searches are among the most important atomic physics experiments as they can strongly constrain theories that go beyond the Standard Model.

In this work, we demonstrate an atomic fountain of laser-cooled Yb atoms for use in precision measurements. The relevant low-lying energy levels of Yb are shown in Fig. 1. As in the case of alkaline-earth elements, there are two transitions that can be used for laser cooling. The strong one is the $^1S_0 \rightarrow ^1P_1$ transition at 399 nm (blue), and the weak one is the $^1S_0 \rightarrow ^3P_1$ intercombination line at 556 nm (green). The hot atoms emanating from an effusive oven are first slowed using a Zeeman slower and then captured in a magneto-optic trap (MOT), both operating on the strong transition. This transition is similar to the laser-cooling transitions in the alkali-metal atoms and has a large capture velocity. We can trap more than $10^7$ Yb atoms in the blue MOT, at a temperature of $\sim 3$ mK for the even isotopes and $\sim 1$ mK for the odd isotopes. The weak transition has a $150\times$ smaller linewidth, which gives a lower MOT temperature but also means the capture velocity is quite small. This makes it difficult to directly load the green MOT from the Zeeman-slowed beam. We therefore transfer atoms captured in the blue MOT into the green MOT. Using a multi-step transfer process, we transfer up to 70% of the atoms and obtain a temperature that is 40 times smaller. The cold atoms from the green MOT are launched against gravity using a pair of green beams in moving-molasses configuration. The launch velocity is varied from 2.1 to 2.9 m/s by adjusting the detuning of the moving-molasses beams.

II. EXPERIMENTAL DETAILS

The main experimental chamber, shown schematically in Fig. 2, consists of three regions: a source region, a Zeeman slower region, and the MOT/fountain region. The source is a quartz ampoule that is resistively heated to about 400°C. The ampoule contains elemental Yb with all the isotopes in their natural abundances. The atomic beam is collimated using a copper skimmer with a small
FIG. 2: (Color online) Experimental chamber. Gravity is along \( z \), and the MOT axis is along \( y \). The 3 sets of MOT beams consist of both blue and green beams, and are produced using a dichroic mirror (DM) as shown in the bottom. Figure abbreviations: BS – beam shutter, M – incoming MOT beam, \( F_{\text{up,down}} \) – fountain beams, Z – Zeeman slowing beam, \( \lambda/4 \) – quarter waveplate.

IV. RESULTS AND DISCUSSION

A. Blue MOT

We first discuss the loading of the blue MOT. The hot atoms emanating from the source have a longitudinal velocity distribution with a most-probable velocity of 310 m/s. All the atoms with velocity below 250 m/s (which represents about 30% of the total number) are slowed down using a spin-flip Zeeman slower. The slower consists of a decreasing field part near the beginning and then an increasing field region near the end. The total slowing distance is 450 mm, and the magnetic field varies from 210 G at the beginning to \(-235 \) G at the end. The slower beam is focussed with a lens so that it has a size of 20 mm near the MOT and 4 mm at the differential pumping tube. The total power in the slowing beam is 20 mW and it is detuned by \(-330 \) MHz from
We define a capture velocity $v_c$ such that atoms having velocity below $v_c$ are cooled and captured in the MOT. From a simple one-dimensional laser-cooling model, $v_c$ is the velocity at which the Doppler shift takes the atom out of resonance by one linewidth, therefore it is given by [11],

$$v_c = (|\Delta| + \Gamma) \frac{\lambda}{2\pi},$$

where $\Delta$ is the detuning of the beams. The value of $\Gamma$ is $2\pi \times 28$ MHz for the blue transition, hence $v_c$ is 22 m/s for a typical detuning of $\Gamma$. Therefore, the Zeeman slower is designed to have a final velocity of 20 m/s, so that all the slowed atoms are loaded into the blue MOT.

The six MOT beams have a total power of 120 mW and size of 15 mm each. The detuning is optimized by looking at the MOT fluorescence, and is around $-40$ MHz at an axial field gradient of 30 G/cm. The $^1S_0 \rightarrow ^1P_1$ transition is not closed since atoms can be lost to the metastable $^3P_{0,2}$ states through the intermediate $D$ states (see Fig. 1). There are also losses due to background collisions in the vacuum chamber. These loss mechanisms limit the trap loading time constant to 1 s. We therefore load the trap for a total time of 2 s. This gives a cold cloud of size 3 mm. By calibrating the MOT fluorescence measured by a photodiode, we estimate the number of atoms to be $10^7$.

The temperature in the MOT is measured by mapping the velocity distribution, which in turn is determined by the absorption of a probe beam using time-of-flight. The probe beam is placed 6 mm below the trap center. If the temperature of the MOT is $T$ and the distance to the probe beam is $d$, then the absorption as a function of time $t$ is given by [12]

$$A(t) \propto \frac{d^3}{t^4} \exp \left( -\frac{M(d/t)^2}{2k_BT} \right),$$

where $M$ is the mass of the atom, and $k_B$ is the Boltzmann constant. In Fig. 3 we show the absorption profile of atoms after they are released from the MOT. The solid curve is a fit to Eq. 2 with the temperature as the only fit parameter. For the even isotope $^{174}\text{Yb}$ with zero nuclear spin, the temperature in the blue MOT is 2.8(9) mK. This is reasonable because the Doppler limit is 0.6 mK, and it is known that the MOT temperature is typically a few times higher than this limit due to additional heating mechanisms [13]. For the odd isotope $^{171}\text{Yb}$ with $I = 1/2$, the presence of magnetic sublevels allows for sub-Doppler cooling. As a result, the measured temperature of 1.0(2) mK is a factor of 3 lower.

B. Green MOT

One would think that the green MOT can be easily loaded from the Zeeman-slowed beam. While this has been done before [14], direct loading is complicated by the narrow linewidth of 182 kHz for this transition. Hence the capture velocity (from Eq. 1) is less than 1 m/s, even if the detuning is 9 $\Gamma$. If the atoms coming out of the slower have this small velocity, the end of the slower has to be less than 10 cm from the MOT center so that atoms do not fall out of the trapping region under the influence of gravity. We have in fact designed such a chamber and loaded atoms into the green MOT directly from the slowed beam. But the number of atoms in the MOT is much less than what we get by first capturing atoms in the blue MOT, and then transferring them into the green MOT. In the following, we discuss this transfer method in detail.

One important difference between the two MOTs is that the optimal field gradient for the green MOT is much smaller than that for the blue MOT. In addition, the transfer efficiency and final MOT temperature are dependent on the detuning and power of the green beams. Therefore the transfer is done in a multi-step process as shown in the sequence in Fig. 4. After the blue MOT is loaded for 2 s, the blue beams are turned off at $t = 0$. Simultaneously the field gradient is lowered from 30 to 7 G/cm. At this time, the green MOT beams have a total power of 30 mW and detuning of $-7$ MHz. After 200 ms, the total power is lowered to 1 mW and the detuning to $-3$ MHz. Finally, after another 200 ms, the total power and detuning are set to their final values of 0.5 mW and $-0.5$ MHz. The percentage transfer is measured by turning the blue MOT beams back on. The fluorescence level at the turn-on point is 0 without...
FIG. 4: (Color online) Sequence for transferring atoms from the blue MOT to the green MOT.

FIG. 5: (Color online) Absorption of a blue probe beam to measure temperature in the green MOT. The solid curve is a fit to Eq. 2 with the temperature as the only fit parameter.

FIG. 6: (Color online) Absorption of a probe beam for atoms launched either with a single pushing beam or two beams in moving-molasses configuration.

The final experiment was to launch the atoms from the green MOT in an atomic fountain. The sequence for launching is the same as that shown in Fig. 4 up to the point of loading of the green MOT, i.e., first loading of the blue MOT for 2 s, then turning off the blue beams and turning down the magnetic-field gradient at \( t = 0 \), and then lowering the power and detuning of the green MOT beams in two steps to get a low final temperature. The launching is done at \( t = 700 \) ms by turning off all the beams and pulsing on the green launching beams for 10 ms. The launched atoms are probed by monitoring the absorption of a blue probe beam placed 19 cm above the MOT center.

The launching can be done with just a single pushing beam or using the idea of moving molasses [8]. With just a pushing beam pointing up, the atoms get heated along this direction. Instead, by using another beam pointing down, the detunings can be chosen such that the atoms are cooled in the launch direction. If we want the detuning to be \(-\Gamma/2\) (which gives the lowest temperature in one-dimensional molasses) in a frame moving up with a velocity \( v \), then the detunings in the laboratory frame are

\[
\Delta_{\text{up}} = \frac{\Gamma}{2} - \frac{v}{\lambda} \quad \text{and} \quad \Delta_{\text{down}} = \frac{\Gamma}{2} + \frac{v}{\lambda}.
\]

(3)

The difference between the two methods of launching is seen in Fig. 6. The absorption of the probe beam as a function of time gives a measure of the longitudinal velocity distribution. There is both a narrowing and an increase in amplitude with the use of moving molasses, clearly indicating cooling in this direction.

The low capture velocity of the green transition, which complicates the direct loading of the MOT, is also a problem with the launching. For a launch velocity of \( v = 2.5 \) m/s, \( \nu/\lambda \) in Eq. 3 is 4.5 MHz, which is 25 times the natural linewidth. Therefore, atoms with 0 velocity will be outside the “capture range” of the beams. To solve this problem, we ramp the detuning of the launch beams from 0 to their final values using AOMs over the launch period of 10 ms. This ensures that the atoms are accelerated adiabatically from 0 to \( v \). The power in each beam is 1 mW, and they are brought to the apparatus.
using single-mode fibers so that there is no change in the direction as the detuning is ramped.

As seen from Eq. (3), the launch velocity can be changed by adjusting the final detunings of the up and down launch beams. In Fig. 7, we show the results of launching $^{171}$Yb atoms at four velocities, ranging from 2.06 m/s to 2.88 m/s. A change in relative detuning $\Delta_{\text{up}} - \Delta_{\text{down}}$ of 800 kHz corresponds to a change in launch velocity by 0.22 m/s. As the velocity decreases, the transverse and longitudinal temperatures become more important since the time to reach the probe beam is longer. As a result, there is increased spread in the signal.

**IV. CONCLUSION**

In conclusion, we have demonstrated launching of laser-cooled Yb atoms in an atomic fountain. The hot atoms emanating from a thermal source are Zeeman slowed and captured in a MOT on the strongly-allowed blue transition. Laser cooling on this transition is similar to cooling of the more common alkali-metal atoms. We capture more than $10^7$ atoms in the blue MOT, with a temperature of about 3 mK for the even isotopes and 1 mK for the odd isotopes. The other laser cooling transition in Yb is a weakly-allowed green transition, which provides not only unique opportunities but also its own problems. In particular, direct loading of the green MOT from a Zeeman-slowed beam is complicated by its small capture velocity. We therefore first capture atoms in the blue MOT and then transfer to the green MOT. The green transition gives a factor of 40 lower temperature in the MOT, but to achieve this the transfer has to be done in a multi-step process with progressively smaller detuning and power in the trapping beams. Under optimal conditions, we can transfer 70\% of the atoms into the green MOT.

The ultracold atoms from the green MOT are launched in an atomic fountain using a pair of green beams in the vertical direction in moving-molasses configuration. This allows us to control the launch velocity without additional heating in the launch direction. Launching atoms in a fountain is again more difficult compared to the alkali-metal atoms because of the small capture velocity of the green transition. We overcome this problem by adiabatically ramping the detuning in the moving-molasses beams, and are then able to launch atoms with velocities varying from 2.1 m/s to 2.9 m/s. The cold atoms can be used for precision measurements such as optical clocks and the search for a permanent atomic EDM. We have recently used a thermal beam of Yb atoms for spectroscopy using the Ramsey separated-oscillatory-fields technique. The application of this idea to a cold atomic fountain should improve the sensitivity by several orders of magnitude.

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