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-optical 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 [1–3] 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 repumping laser. In addition, it has seven stable isotopes, of which five are bosonic and two are fermionic. This allows the comparative study of Fermi-Bose gas mixtures, particularly under conditions of quantum degeneracy [4,5]. 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 [6]. Yb has been used to observe, by far, the largest parity-violating effect in an atom [7]. One of us (V.N.) has recently proposed [8] 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 paper, 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-optical 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. Therefore, we transfer atoms captured in the blue MOT into the green MOT. Using a multistep 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 [9]. 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 hole, and has a pneumatic shutter in front of it. The source region is pumped with a 20-l/s ion pump so that the pressure is below 10^{-7} torr when the source is on.

The source region is connected to the Zeeman-slowing region using a small differential pumping tube, which allows the experimental chamber to be at much lower pressure and also provides further collimation. The slower is a tube of 40-mm diameter by 500-mm length. The required magnetic-field profile is generated by winding welding cables on the outside. At the end of the slower is the main MOT chamber. The distance to the center of the MOT is 220 mm. The MOT chamber consists of eight small (70-mm diameter) ports in the x-z plane and two large (100-mm diameter) ports along the y direction. The ports along z, which is the direction of gravity, have the fountain chamber. The ports along x are used to connect to the Zeeman slower on one side and a 55-l/s ion pump on the other side. The pressure in the MOT region is below 10^{-9} torr. Optical access is provided by glass viewports, while the fountain chamber is a rectangular glass cell.

From the energy-level diagram, we see that the experiment requires two main lasers. The blue beam at 399 nm is produced by using a ring Ti:sapphire laser (Coherent 899-21) operating at 798 nm and doubling its output in an external δ-cavity doubler (Laser Analytical Systems LAS100). The

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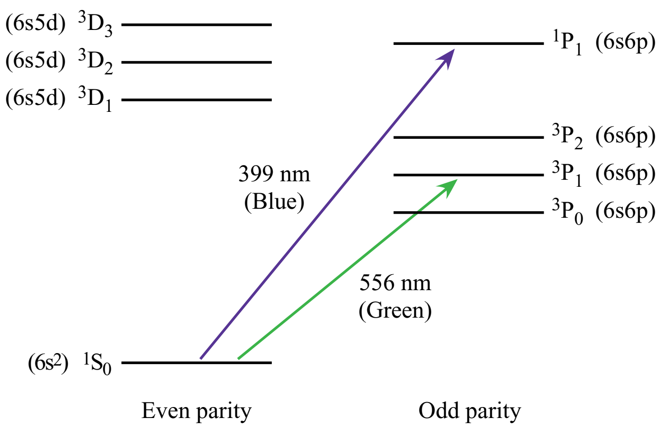

FIG. 1. (Color online) Low-lying energy levels of Yb showing the two transitions that can be used for laser cooling and trapping.

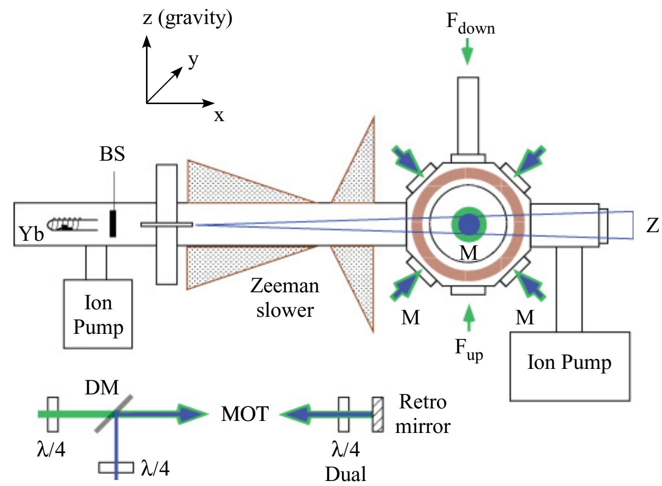

FIG. 2. (Color online) Experimental chamber. Gravity is along z, and the MOT axis is along y. The three sets of MOT beams consist of both blue and green beams, and are produced using a dichroic mirror (DM) as shown in the bottom. Figure abbreviations: BS, beam shutter; M, incoming MOT beam; $F_{\mathrm{up,down}}$, fountain beams; Z, Zeeman slowing beam; $\lambda/4$, quarter-wave plate.

output power of the Ti:sapphire is 1.5 W, and its frequency is stabilized on a reference cavity to give an rms linewidth of 1 MHz. The output of the doubler is about 180 mW. Of this, 30–40 mW is sent through an acousto-optic modulator (AOM) for the Zeeman-slowing beam. The remaining power is used to produce the MOT beams. A second low-power blue beam used for probing is generated using a 30-mW diode laser (Nichia Corporation) stabilized in an external grating-feedback cavity. The linewidth after stabilization is about 1 MHz, and the output power is 9 mW. The green beam at 556 nm is produced by doubling the output of a fiber laser operating at 1111 nm (Koheras Boostik Y10). The output power of the fiber laser is 500 mW with a linewidth of 70 kHz. The frequency is doubled in an external ring cavity (Toptica Photonics) with a temperature-tuned $KNbO_3$ nonlinear crystal. The output power of the doubler is 65 mW.

The MOT is made of three sets of counterpropagating beams, two in the x-z plane and one along the y direction. The quadrupole magnetic field is along the y direction. Each MOT beam is composed of a circularly polarized blue beam and a circularly polarized green beam, mixed on a DM. The combined beams retroreflect on the other side of the chamber through a dual-wavelength $\lambda/4$ wave plate.

The frequency of the blue laser from the doubler is manually adjusted to maximize the MOT fluorescence and then left untouched during the MOT loading time of a few seconds. Since the drift of the Ti:sapphire laser is less than 10 MHz/h, the laser does not need to be actively locked. On the other hand, the blue diode-laser beam used for probing and the green beam are locked to their respective transitions. The spectroscopy for locking is done in a separate vacuum chamber that also has a collimated Yb atomic beam. The laser beams are sent perpendicular to the atoms, and the fluorescence is collected by two photomultiplier tubes (Hamamatsu R928). The blue laser is locked using modulation-free locking [10]. The error signal is generated by taking the difference between opposite circular polarizations in the presence of a magnetic field (circular dichroism). The green laser is locked to a peak by frequency modulation at 20 kHz and lock-in detection to generate the error signal.

III. 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 [11]. 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 focused 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 resonance.

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 [12],

$$v_c = (|\Delta| + \Gamma)\,\frac{\lambda}{2\pi}, \qquad (1)$$

where Δ is the detuning of the beams. The value of Γ is $2\pi \times 28$ MHz for the blue transition, hence, v_c is 22 m/s for a typical detuning of Γ. 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.

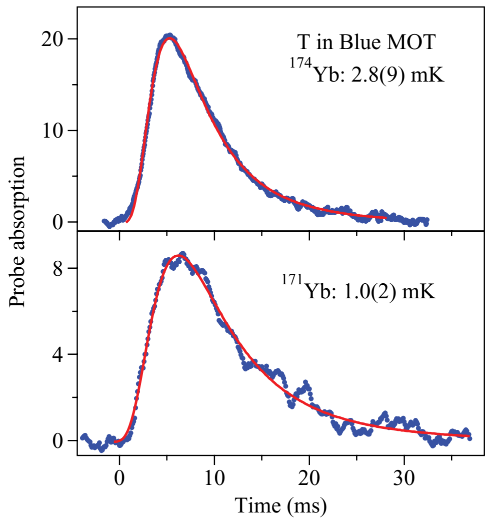

FIG. 3. (Color online) Absorption profile of a blue probe beam used to measure the temperature in the blue MOT. The solid curve is a fit to Eq. (2) with the temperature as the only fit parameter.

These loss mechanisms limit the trap loading time constant to 1 s. Therefore, we 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 [13]

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

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}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 [14]. For the odd isotope ^{171}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 [15], 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 9Γ. 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.

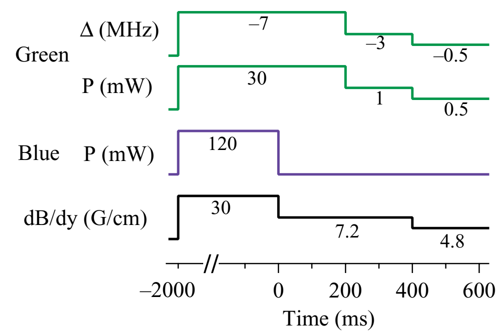

FIG. 4. (Color online) Sequence for transferring atoms from the blue MOT to the green MOT.

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 multistep 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, respectively. The percentage transfer is measured by turning the blue MOT beams back on. The fluorescence level at the turn-on point is 0 without the green MOT, and jumps to some fraction of its original value with the MOT on, indicating that these many atoms have survived in the green MOT. Under optimal conditions, we can transfer 70% of atoms from the blue to the green MOT.

The main advantage of the green MOT is the lower final temperature attained by the atoms. This is because the Doppler limit for this narrow transition is only 4.4 μK. This advantage is evident from the temperature measurement shown in Fig. 5. For the even isotope ^{174}Yb with no sub-Doppler cooling, the temperature is 66(4) μK, a factor of 40 lower than that in the blue MOT. The temperature for the odd isotopes is not shown, but is again three times smaller due to sub-Doppler cooling [16].

C. Atomic fountain

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

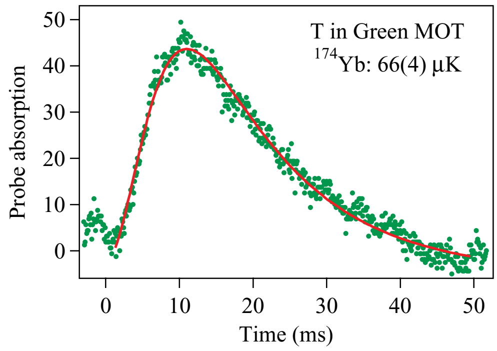

FIG. 5. (Color online) Absorption of a blue probe beam to measure temperature in the green MOT. The solid curve is a fit to Eq. (2) with the temperature as the only fit parameter.

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 [9]. 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

$$\Delta_{\rm up} = \Gamma/2 - v/\lambda \quad \text{and} \quad \Delta_{\rm down} = \Gamma/2 + v/\lambda. \qquad (3)$$

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, v/λ 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

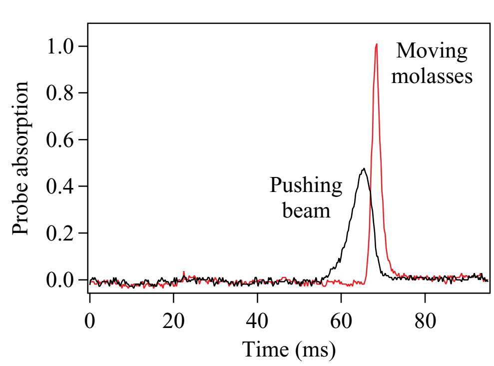

FIG. 6. (Color online) Absorption of a probe beam for atoms launched either with a single pushing beam or with two beams in moving-molasses configuration.

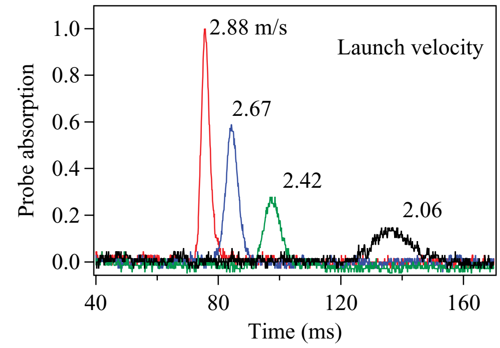

FIG. 7. (Color online) Absorption of a probe beam for ^{171}Yb atoms launched with different velocities.

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 to 2.88 m/s. A change in relative detuning $\Delta_{\rm up} - \Delta_{\rm down}$ 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. Therefore, we 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 multistep 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 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-field technique. The application of this idea to a cold atomic fountain should improve the sensitivity by several orders of magnitude.

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