

Cold beam of isotopically pure Yb atoms by deflection using 1D-optical molasses

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Abstract. We demonstrate the generation of an isotopically pure beam of laser-cooled Yb atoms by deflection using 1D-optical molasses. Atoms in a collimated thermal beam are first slowed using a Zeeman slower. They are then subjected to a pair of molasses beams inclined at 45° with respect to the slowed atomic beam. The slowed atoms are deflected and probed at a distance of 160 mm. We demonstrate the selective deflection of the bosonic isotope ^{174}Yb and the fermionic isotope ^{171}Yb . Using a transient measurement after the molasses beams are turned on, we find a longitudinal temperature of 41 mK.

Keywords. Laser cooling; cold atoms; atomic beam; optical molasses.

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1. Introduction

Cold atoms [1], with their long measurement times, promise to revolutionize the field of precision measurements. In this respect, laser-cooled Yb constitutes a useful species because its spin-zero ground state obviates the need for a second re-pumping laser, as is required for laser cooling of the more common spin-half alkali-metal atoms. As a consequence, cold Yb has been proposed for use in next-generation atomic clocks [2,3] and the search for a permanent electric dipole moment (EDM) [4]. Existence of an EDM is an indication of both parity violation (which is already known from the weak interaction) and time-reversal symmetry violation in the fundamental laws of physics, and is one of the most important experiments in atomic physics today. As a consequence, EDM measurements have been reported in ^{199}Hg [5], ^{133}Cs [6], ^{205}Tl [7], TlF [8], ^{174}YbF [9], etc. Both clock and EDM measurements gain from having a cold continuous beam of atoms that is separated from the cooling laser beams. For atomic clocks, a continuous beam avoids intermodulation or the Dick effect [10], seen in pulsed fountain clocks. For EDM experiments, the electric-field plates can be brought very close because there is no interference from any laser beams.

Here, we demonstrate such a continuous beam by deflection, using a pair of 1D-optical molasses beams. Atoms emanating from a thermal source are first cooled and slowed in a Zeeman slower. The molasses beams are inclined at 45° , and chosen to be nearly resonant with one particular isotope. Thus, the deflected atomic beam is isotopically pure, and free from both other isotopes and unslowed atoms. The deflected atoms are probed at a distance of 160 mm from the molasses region. We verify that any selected isotope can be deflected: ^{174}Yb as an example of an even isotope and ^{171}Yb as an example of an odd isotope. A transient measurement after the molasses beams are turned on, shows a mean velocity of 15.55 m/s, and a longitudinal temperature of 41 mK. This temperature represents a factor of three improvements over our recent work in which atoms were launched vertically from a two-dimensional magneto-optic trap (2D-MOT) [11]. Compared to the earlier experiment, the current set-up has the additional advantage of being easier to implement.

2. Experimental details

Many of the experimental details are similar to our earlier work in ref. [11], and are presented here for completeness. Yb has two cooling transitions – the strongly-allowed $^1S_0 \rightarrow ^1P_1$ transition at 399 nm, and the weakly-allowed $^1S_0 \rightarrow ^3P_1$ intercombination line at 556 nm – as shown in figure 1. In this study (as in our previous work), we have

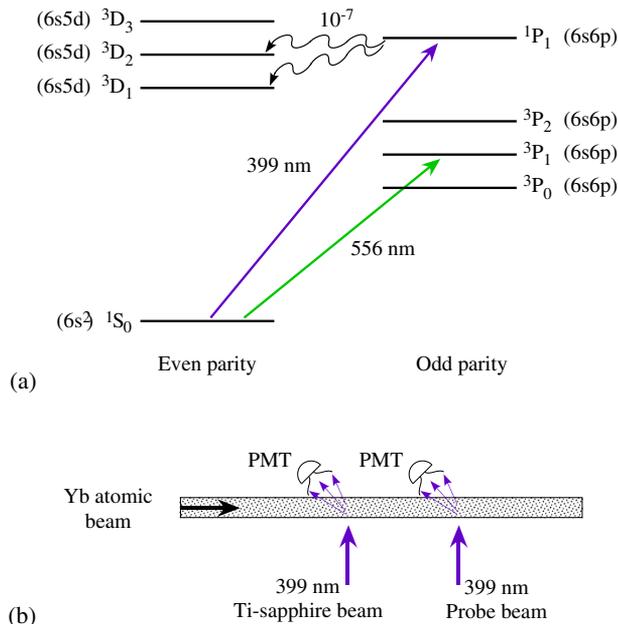


Figure 1. (a) Low-lying energy levels of Yb. Even-parity levels are shown on the left and odd-parity levels on the right. Therefore, only transitions between the left manifold and right manifold are electric-dipole-allowed. (b) Spectroscopy arrangement used to determine the frequency of the lasers.

only used the former one. Though, its relatively large linewidth of 28 MHz implies a large Doppler-cooling temperature of $690 \mu\text{K}$, it allows for Zeeman slowing over a short distance. The saturation intensity for this transition is 58 mW/cm^2 . Two of the nearby triplet- D states are lower in energy than the 1P_1 state. So the transition is not really closed, but the branching ratio of 10^{-7} to these states is negligibly small [12]. For example, the number of photons required to slow an atom from 300 to 25 m/s is less than 10^5 . The two isotopes used in this study are ^{174}Yb (boson with $I = 0$) and ^{171}Yb (fermion with $I = 1/2$). Therefore, the isotope, ^{174}Yb has a single hyperfine transition from $F = 0 \rightarrow F' = 1$. The other isotope, ^{171}Yb has two transitions: $F = 1/2 \rightarrow F' = 1/2$ and $F = 1/2 \rightarrow F' = 3/2$. The Zeeman shifts for the $0 \rightarrow 1$ transition in ^{174}Yb and the $1/2 \rightarrow 3/2$ transition in ^{171}Yb , both have the same value of 1.4 MHz/G. Hence, the same Zeeman-slower profile and the slower-beam de-tuning can be used for both isotopes.

The main laser for accessing the 399 nm transition is generated in a two-step process. We start with a single-frequency Ti:sapphire laser (Coherent 899-21) operating at 798 nm, pumped with 532 nm light (Spectra Physics Millennia X). Its output is frequency-doubled to 399 nm in an external-cavity doubler with a lithium triborate crystal (Laser Analytical Systems), with a conversion efficiency of about 12%. The output of the doubler is split into three parts: the first part for the Zeeman-slowing beam, the second part for the 1D-molasses beams and the third part to monitor its frequency in the fluorescence spectroscopy set-up shown in figure 1b. The fluorescence light is collected using a Hamamatsu R928 photomultiplier tube (PMT). The laser frequency is manually adjusted to be at the fluorescence peak, and left there for the duration of the experiment. The drift of the Ti:sapphire laser is small enough that there is no significant movement away from the peak. The frequency shift required for the Zeeman-slowing and molasses beams are produced using acousto-optic modulators (AOMs). The deflected atoms are probed using a second low-power laser, composed of a grating-stabilized diode laser (Nichia Corporation). Its frequency is also monitored in the same spectroscopy set-up using a second PMT.

A top-view schematic of the vacuum system used in the experiment is shown in figure 2. The source of atoms is a resistively-heated quartz ampoule containing all the isotopes of Yb in their natural abundance. The source region is maintained at a pressure below 10^{-7} torr using an ion pump of 20 l/s speed. This region is attached to the experimental

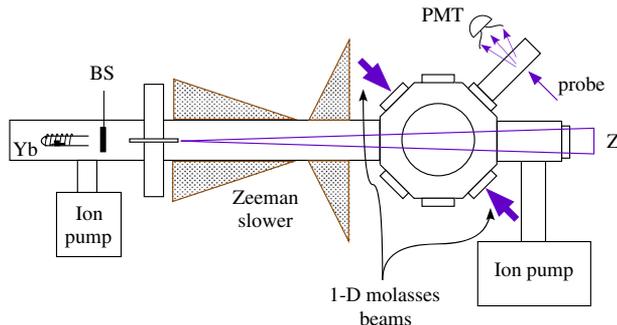


Figure 2. Top view schematic of the vacuum chamber used for the experiment. Detailed description is given in the text. Z: Zeeman-slower beam, BS: beam shutter.

chamber through a differential-pumping tube, so as to allow for a pressure difference of two orders of magnitude. The first part is a Zeeman-slowing region, consisting of a stainless-steel (SS) tube with OD = 42 mm and length = 500 mm. The second part is the main experimental chamber, consisting of an octagonal SS cell in the horizontal plane with two 70 mm viewports for the 1D-molasses beams. This region has a pressure of 10^{-9} torr. The port at 45° with respect to the direction of the atomic beam has a rectangular glass cell for probing the deflected atoms. The probe region is at a distance of 160 mm from the deflection point, and the fluorescence signal is collected with a third PMT. The entire system on this side of the differential pumping tube is pumped by a second ion pump with 55 l/s speed.

Atoms emanating from the oven are first slowed in a spin-flip Zeeman slower [13], i.e. one with a positive initial field and a negative final field going through zero in between. The main advantage of this design is that the field coils do not carry much current, and do not require active cooling. With a de-tuning of -420 MHz and an initial field of $+290$ G, the slower is designed to slow all atoms with an initial velocity upto 330 m/s. This corresponds to capturing of 55% of the atoms emanating from the oven, when it is heated to 400°C . The final field at the end of the 0.33 m long slower is -260 G, which means that the velocity after the slower is 23 m/s. The coils required for generating the slower-field profile are made by winding welding wire around the outside of the Zeeman-slower tube. The wire carries 34 A for the forward slower and 26 A for the reverse part. The slowing beam is circular, with $1/e^2$ diameter of 30 mm at the entrance to the octagonal chamber, and focussed to a spot at the end of the differential-pumping tube using a convex lens of 1 m focal length.

The incoming molasses beam has a total power of 46 mW. Its cross-section is elliptic, with $1/e^2$ diameter of 10×15 mm, and the long axis aligned in the vertical direction. Therefore, the peak intensity at the beam centre is 78 mW/cm^2 , to be compared with the saturation intensity of 58 mW/cm^2 . The beam has a detuning of -14 MHz ($= -\Gamma/2$ for this transition), which is known to give the lowest temperature for optical molasses [14]. It is linearly polarized. The return beam is generated by retro-reflecting the incoming beam with a plane mirror. As the velocity of the atoms after the slower is 23 m/s, and the molasses beams are inclined at an angle of 45° , the expected mean velocity of the deflected atoms is $23/\sqrt{2} = 16.26$ m/s.

The experimental parameters used in this study are summarized in table 1.

3. Results and discussion

The first experiment was to make sure that the deflected atoms were isotopically pure. The deflected isotope was either ^{174}Yb (as an example of a boson) or ^{171}Yb (as an example of a fermion). The main Ti-Sa laser was brought into resonance with the desired isotope,

Table 1. Experimental parameters used in the experiment.

Zeeman-slower beam power	10 mW
Zeeman-slower beam detuning	-420 MHz
1D-molasses beam intensity (max.)	78 mW/cm^2
1D-molasses beam detuning	-14 MHz

and the probe laser was scanned across the same isotope. The PMT signal for the two isotopes is shown in figure 3. The two peaks for ^{171}Yb correspond to the $1/2 \rightarrow 3/2$ and $1/2 \rightarrow 1/2$ transitions.

There are two points to note about the spectra. One is that the linewidth of the peaks is 44 MHz, which is 1.5 times the natural linewidth of 28 MHz. This is typical for the spectra seen in our previous work [15,16], and is due to power broadening and transverse temperature. The second point is that the peak height for ^{174}Yb is 3.5 times larger than the $1/2 \rightarrow 3/2$ peak in ^{171}Yb , resulting in correspondingly higher signal-to-noise ratio (SNR). This is again similar to the ratio of these two peaks seen in our earlier work, and is due to a combination of the smaller natural abundance and hyperfine structure for ^{171}Yb .

The second experiment was designed to measure longitudinal temperature in the deflected atomic beam. For this, we consider the fluorescence signal as a function of time after the molasses beams are turned on. The only isotope studied was ^{174}Yb . The probe laser is now locked to this resonance peak. The measured signal is therefore determined by both the mean velocity and the longitudinal spread around the mean velocity or temperature. If the mean velocity is \bar{v} and the distribution follows a Maxwell–Boltzmann curve at a temperature T , then the probability density function is

$$f(v) = \sqrt{\frac{m}{2\pi k_B T}} \exp\left[-\frac{m(v - \bar{v})^2}{2k_B T}\right], \quad (1)$$

so that $f(v) dv$ is the probability of the atom to have a velocity between v and $v + dv$.

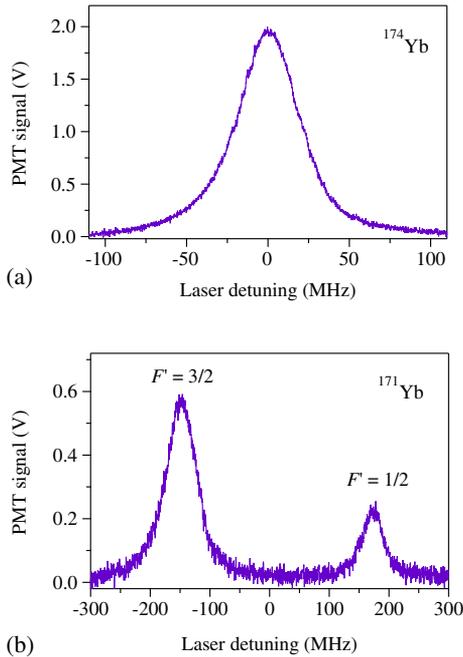


Figure 3. Fluorescence signal from deflected atoms in the probe region of (a) ^{174}Yb and (b) ^{171}Yb . There are two peaks for ^{171}Yb because it has two hyperfine levels in the excited state, with F' values as labelled.

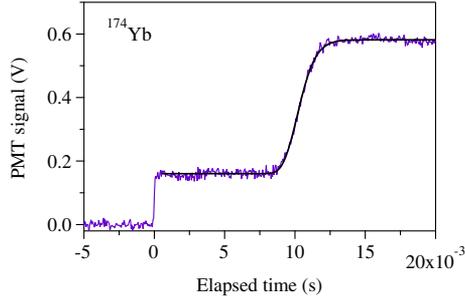


Figure 4. Fluorescence signal of ^{174}Yb atoms in the probe region as a function of elapsed time after the 1D-optical molasses beams are turned on. The probe laser is locked to the resonance peak. The sudden jump at $t = 0$ is due to stray light from the molasses beams making it to the PMT. The smooth line is a curve fit to the expected line shape (eq. (2) in the text).

The measured signal is proportional to the total number of atoms in the probe region at a given time t . If the distance to this region from the deflection region is d , then all atoms having an initial velocity greater than d/t will contribute to the signal. Therefore, the signal at a time t is proportional to the integral of the above distribution from d/t to ∞ , i.e.

$$N(t) = N_0 \operatorname{erfc} \left[\sqrt{\frac{m}{2k_B T}} \left(\frac{d}{t} - \bar{v} \right) \right]. \quad (2)$$

We neglect the effect of gravity because the distance by which atoms fall in the time it takes to reach the probe region is about 0.5 mm, which is much smaller than the probe-beam diameter.

The results of this experiment are shown in figure 4. The jump in signal at $t = 0$ is due to this stray light from the molasses beams making it to the PMT. The smooth line is a curve fit to the line shape given in eq. (2). The fit yields a mean velocity of $\bar{v} = 15.52(2)$ m/s, consistent with the expected value of 16.26 m/s. The spread around the mean is 1.98(3) m/s. This corresponds to a longitudinal temperature of 41(1) mK, which represents an improvement of a factor of 3 over our previous work in ref. [11].

4. Conclusion

In summary, we have demonstrated the creation of an isotopically pure cold beam of Yb atoms by deflection using 1D-optical molasses. A continuous cold beam has many advantages over the more common pulsed fountain for precision measurements. Yb atoms emanating from a thermal source are first slowed in a Zeeman slower, then deflected using a pair of molasses beams inclined at 45° with respect to the slowed atomic beam. The deflected atoms have a longitudinal temperature of 41 mK, which is more than three times better than our previous experiment [11]. The atoms in this study were deflected using molasses in one direction, and we hope to increase the flux by using an additional set of molasses beams orthogonal to the plane of octagonal cell and hence, the atomic beam – a configuration called 2D-optical molasses.

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