Zeeman slowing of thulium atoms

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Cooling of any new atomic species opens new horizons for spectroscopy, atomic and quantum physics, degenerate gas study and some technical applications. Compared to buffer gas cooling demonstrated for a variety of atoms and molecules (see e.g. [1]), laser cooling is not universal, but gives more selectivity and control on atoms also typically allowing for lower temperatures. Depending on the level structure and atomic properties as well as availability of laser sources, an individual approach to each element is necessary.

Lanthanides with their peculiar level structure are of special interest for cooling and trapping [1–3]. Laser-cooled ytterbium with the closed 4f shell is readily used in laboratories for degenerate gas studies [4] and optical frequency metrology [5]. In 2006 erbium atoms with a much more complex level structure were successfully laser cooled and trapped [6], sub-Doppler cooling was demonstrated [7] and a new type of magneto-optical trap (MOT) was reported [8].

In 2007 we studied laser cooling transitions in atomic thulium [9]. Tm has only one stable bosonic isotope (169Tm, the nuclear spin number is I = 1/2) and a single vacancy in the 4f shell. There are two components of the ground-state fine splitting with the electronic momentum quantum numbers of J = 7/2 (the lower one) and J = 5/2 (the upper one) separated by 2.6 × 10^{14} Hz. The magnetic dipole transition between these levels at 1.14 μm is of particular interest for high precision frequency measurements since it is highly immune to external perturbations [1,10] and has a Q-factor of 2 × 10^{14}. This relativistic transition is highly sensitive to an α variation (its energy scales as α^2 Ry, α is the fine structure constant, Ry is the Rydberg constant) and can be used in the laboratory search for the α drift [11,12].

Our previous study [9] showed that laser cooling should be feasible using the strong transition at 410.6 nm between the ground state 4f^136s^2(2F^5)/(J = 7/2, F = 4) and the excited state 4f^12(3H_5)5d_3/26s^2(J = 9/2, F = 5) with a natural line width of γ = 10.5(2) MHz (F is the total momentum quantum number). The transition is not completely cycling since the upper level decays to 6 neighboring opposite-parity levels. The calculations showed that the branching ratio is at the 10^{-5} level which is small enough for efficient deceleration of atoms. Similar to the case of Er [6], no need for a repumping laser is expected. In this Letter we demonstrate one-dimensional laser cooling of a thulium atomic beam with the help of a Zeeman slower.

The experimental setup is shown in Fig. 1. Thulium metal is sublimated in a home-made sapphire oven (oven 1) at a temperature of 1100 K measured by a platinum resistor. An atomic beam with an intensity estimated as 10^9 atoms per second is formed by two diaphragms. The low-vacuum region containing the oven is pumped by a 301/s turbo-molecular pump and is separated by the diaphragm D1 (3 mm in diameter and 2 cm long) from the rest of the vacuum chamber pumped by a 301/s ion-getter pump. Atoms pass the decelerating region and enter a 6-way-cross vacuum chamber through the second diaphragm D2 with a diameter of 5 mm. The two vacuum volumes may be separated by a valve V.

The second harmonic of a Ti:sapphire laser is tuned to the transition at 410.6 nm. As a reference we use the sat-

Fig. 1. Schematic of the setup. Here TMP is a turbo-molecular pump, D1 and D2 are diaphragms collimating the atomic beam, V is a blocking valve, and AOM is an acousto-optical modulator. Atoms may be excited either by the probe beam 1 at 90° or by the probe beam 2 at 45° in respect to their velocity. Luminescence photons coming from the center of the cross are detected by a photomultiplier orthogonal to the plane of the drawing (not shown).
uration absorption signal (Fig. 2 (bottom)) from the oven 2 at 900 K containing Tm chunks. The laser frequency may be either freely scanned or locked to the saturation absorption signal shifted by an acousto-optical modulator (AOM 1) working in the +1 order at the frequency $\nu_1$. For locking we use the cross-over resonance between the hyperfine 4 $\leftrightarrow$ 5 and 3 $\leftrightarrow$ 4 transitions residing at $+180$ MHz from the cooling 4 $\leftrightarrow$ 5 transition. The laser frequency $f_L$ is thus given by $f_L = f_c - \nu_1 + 180$ MHz, where $f_c$ is the frequency of the cooling transition.

The second AOM2 working in the $-1$ order (Fig. 1) at the frequency $\nu_2$ forms the slowing light beam which is detuned from the cooling transition by $\Delta f_c = 180$ MHz $- \nu_1 - \nu_2$ if the laser is locked to the cross-over resonance. The $g$-factors of the lower and the upper level nearly coincide, the resulting sensitivity for $\sigma$-polarized light is $1.46$ MHz/G. For the Zeeman slower design taken from [13] the red detuning $\Delta f_c$ of the slowing beam should be in the range from $-130$ MHz to $-190$ MHz depending on the desirable velocity of decelerated atoms.

A part of the beam is used as $90^\circ$ probe (probe beam 1) which crosses the atomic beam at the center of the chamber. The luminescence photons are collected in the third direction and focused on a photomultiplier (PMT). A typical Doppler-free luminescence signal taken by scanning of the laser frequency (in this case the laser is not locked) is shown in Fig. 2 (top). The observed line widths are consistent with the natural line width $\gamma$. Imperfections of the probe beam 1 adjustments result in a frequency uncertainty of the recorded lines of $5$ MHz.

The 40-cm Zeeman slower consists of two coils of opposite polarity [6, 13]. The outer coil consists of seven wire layers of different lengths which effectively form 7 sections, while the inner one has two sections. The outer coil (shown in black in Fig. 1) and the inner coil (gray) are fed independently by currents $I_{out}$ and $I_{in}$ respectively. The measured axial magnetic field distribution in the slower is shown in Fig. 3 (left). The currents mostly affect the number of slowed atoms rather than their final velocity. The values shown in the figure are experimentally optimized currents for the slower tuned to the velocity $25$ m/s (see further).

Computer simulations of our Zeeman slower show that one can decelerate $10-18\%$ of atoms from the atomic beam at the temperature $T = 1100$ K to the velocity range of 10-40 m/s. An example is shown in Fig. 3 (right) with the magnetic field distribution taken from Fig. 3 (left). We assume a homogeneous radial light field distribution with an intensity of $20I_{sat}$, where $I_{sat} = 6.1$ mW/cm$^2$ is the saturation intensity. The detuning equals $\Delta f_c = -140$ MHz. Leaking of the atomic population to the “dark” states, losses on diaphragms and optical pumping from the $F = 3$ sublevel are not taken into account. In this case about $10\%$ of Tm atoms are decelerated to the velocities around 20-25 m/s.

The longitudinal velocity distribution of Tm atoms in the beam $N_{0}(v_x)$ is probed by the laser probe beam 2 directed at $45^\circ$ to the atomic beam (Fig. 1). The waist radius ($1/e^2$) and the power of the probe beam are $1.6$ mm and $0.85$ mW correspondingly. To analyze the velocity distribution we record the luminescence spectrum of the Tm beam by scanning the laser frequency with the Zeeman slower switched off. The result of this measurement is shown in Fig. 4. To recover the velocity distribution one should take into account the interaction time with the laser beam $\propto 1/v_x$. The PMT was operating in the current measuring regime to avoid non-linearities of the photon counting. After the measurement the signal was calibrated.

The measured velocity distribution deviates from the thermal distribution in a one-dimensional beam ($\propto v_x^3 \exp(-mv_x^2/2kT)$), where $m$ is the Tm atomic mass,
The peak in Fig. 4 demonstrates the operation of the Zeeman slower optimized for 25 m/s. To remove the background, two signals with the magnetic field switched on and off are subtracted. Taking into account the measured PMT sensitivity of $2 \times 10^7$ photon s$^{-1}$ V$^{-1}$, the photon collecting efficiency of $7 \times 10^{-3}$ and the photon scattering rate in the probe beam 2 of $2.5 \times 10^7$ s$^{-1}$ (averaged over the probe beam profile) we evaluate the flow of slow atoms through the probe beam cross-section as $3 \times 10^6$ s$^{-1}$. The vertical size of the cross-section is the probe beam diameter (3.2 mm at 1/e$^2$), while its horizontal size equals the atomic beam diameter and is evaluated as 1 cm. The latter results from the diaphragms geometry and the angular spreading of slowed atoms after the Zeeman slower. We evaluate the flux of the slowed atoms as $\approx 10^7$ s$^{-1}$ cm$^{-2}$.

Comparing the count rates in the 25 m/s peak with the total velocity distribution taken at similar experimental conditions (Fig. 4), the fraction of slowed atoms is evaluated as 1 % which is less than expected from the simulation (Fig. 3). The difference is mainly explained by the excessive angular spread of slow atoms at the exit of the Zeeman slower which results in losses on diaphragm D2 and a change of the atomic beam cross-section at the detection region. There are other effects which may influence the ratio, e.g. the decay of the upper cooling level $4f^2(3H_2)5d_3/2s^2$($J = 9/2, F = 5$) to highly excited odd parity levels [9] and repumping from the other ground-state hyperfine component $F = 3$ by the cooling laser. Evaluations are consistent with the experimental data. We demonstrated, that the velocity of slowed atoms can be varied in the range 20-40 m/s by changing the detuning $\Delta f_c$ with corresponding optimization of the magnetic field.

In conclusion, we have decelerated Tm atoms from a hot beam by laser cooling at 410.6 nm to the velocity range 20-40 m/s. The beam of slow atoms of 1 cm in diameter has a flux of $10^7$ s$^{-1}$ cm$^{-2}$ which should be enough for capturing a cloud of $10^5$ Tm atoms in a MOT. No repumping laser is necessary as in the case of laser cooling of Er [6].

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