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# Magneto-optical trap for thulium atoms

D. Sukachev,* A. Sokolov,* K. Chebakov, A. Akimov,* S. Kanorsky, N. Kolachevsky,† and V. Sorokin*

*P.N. Lebedev Physical Institute, Leninsky Prospekt 53, 119991 Moscow, Russia*

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Thulium atoms are trapped in a magneto-optical trap using a strong transition at 410 nm with a small branching ratio. We trap up to $7 \times 10^4$ atoms at a temperature of 0.8(2) mK after deceleration in a 40-cm-long Zeeman slower. Optical leaks from the cooling cycle influence the lifetime of atoms in the magneto-optical trap which varies between 0.3 and 1.5 s in our experiments. The lower limit for the leaking rate from the upper cooling level is measured to be 22(6) $s^{-1}$. The repumping laser transferring the atomic population out of the $F = 3$ hyperfine ground-state sublevel gives a 30% increase for the lifetime and the number of atoms in the trap.

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Laser cooling and trapping of neutral atoms is one of the most powerful tools for studying atomic ensembles at ultralow temperatures [1]. It has opened a new era in precision laser spectroscopy [2], the study of collisions [3], atomic interferometry [4], and the study of quantum condensates [5,6]. Compared to buffer gas cooling [7], much lower temperatures may be reached, although laser cooling strongly depends on an atomic level structure and the availability of laser sources.

Since the very first experiments on laser deceleration of sodium atoms [8,9] alkali metals remain the most popular objects for laser cooling. Today all alkali-earth-metal atoms and noble gases in the metastable state (except Rn) are successfully laser cooled and trapped in magneto-optical traps (MOTs). The family of laser-cooled species is continuously growing, with laser cooling and trapping of Er [10], Cd [11], Ra [12], Hg [13], and Dy [14] being reported in the last few years. These new cold species find applications in metrology, quantum information, tests of fundamental theories, and degenerative gas studies.

We have demonstrated laser cooling and trapping of thulium atoms in a MOT at a wavelength of 410.6 nm. This lanthanide possesses only one stable bosonic isotope, $^{169}$Tm, with nuclear spin quantum number $I = 1/2$. After Yb [15], Er [10], and Dy [14] it is the fourth lanthanide that has been trapped in a MOT. Lanthanides with unfilled $4f$ electronic shell are especially interesting due to the following peculiarities.

First, their ground-state magnetic moment is much larger than that of the alkali metals. The dipole moment of $^{169}$Tm is 4 $\mu_B$ (here $\mu_B$ is the Bohr magneton), for Er it approaches 7 $\mu_B$, and for Dy it is 10 $\mu_B$. Such strongly magnetic atoms may be used in studies of dipole-dipole interactions [16] and interactions with superconductors [17]. Physics of cold polar molecules [18] may also benefit from using a strongly magnetic atom in molecular synthesis.

Second, the ground state $4f^n6s^2$ of such atoms is split into a number of fine-structure sublevels separated by large, up to optical, frequency intervals. The fine structure of the thulium ground state $4f^{13}6s^2$ consists of two sublevels with the total electronic momentum quantum numbers $J = 7/2$ and $5/2$. These sublevels are optically coupled by a narrow (the spectral linewidth of 1.2(4) Hz [19]) magnetic dipole transition at 1.14 $\mu$m (Fig. 1). The upper sublevel, being a long-lived metastable optically addressable state, is potentially suitable for applications in quantum memory [20–22].

Outer closed $6s^2$ and $5s^2$ shells strongly shield the transition at 1.14 $\mu$m. Experiments with magnetically trapped atoms [7] and with atoms implanted in a solid matrix [23] have shown a dramatic reduction in the sensitivity to collisions with noble gases and perturbations by electric fields. This transition also may be used in the detailed study of Tm-Tm long-range quadrupole-quadrupole interactions [24] and in the search for the fine-structure constant variation ($\dot{\alpha}/\alpha$) because of its quadratic $\alpha$ dependence [25].

Formerly we have studied candidates for laser-cooling transitions in thulium [19]. A theoretical analysis of the leak rates from the cooling cycle indicated that the most favorable for the first cooling step is a $4f^{13}6s^2(J = 7/2, F = 4) \rightarrow 4f^{12}5d6s^2(J' = 9/2, F' = 5)$ transition at 410.6 nm with the natural linewidth of $\gamma = \Gamma/2\pi = 10(4)$ MHz, where small and capital letters denote rates in Hz and radians per second, respectively. Here $F$ and $F'$ denote the total atomic momentum quantum numbers for ground and excited states, respectively. In 2009 we demonstrated the Zeeman deceleration of a Tm thermal beam by using laser radiation at 410.6 nm without a repumping laser [26]. The presence of the decay channel from the upper cooling level (Fig. 1) did not prevent efficient deceleration, indicating the feasibility of the further cooling and trapping of atoms.

To trap Tm atoms we use a classical MOT configuration with three orthogonal pairs of antipropagating cooling laser beams as shown in Fig. 2. The MOT chamber is a six-beam cross with additional ports for a Zeeman slower and detectors. The chamber is pumped by a 30 l/s ion-getter pump to a pressure less than $10^{-8}$ mbar. Two coils in the anti-Helmholtz configuration produce an axial field gradient up to 10 G/cm in the center of the chamber. The laboratory magnetic field is compensated by additional coils.

The MOT is loaded from an atomic beam decelerated in the Zeeman slower. Tm vapors are produced in a homemade sapphire oven at a temperature 1100 K, which is much lower than the melting point (1818 K). This temperature provides a sufficient atomic flow from the oven (the corresponding saturated vapor pressure is about $10^{-2}$ mbar). The oven is separately pumped by a 30 l/s turbo-molecular pump to $10^{-7}$ mbar.

*Also at Moscow Institute of Physics and Technology, 141704 Dolgoprudny, Moscow region, Russia.

†kolik@lebedev.ru

 

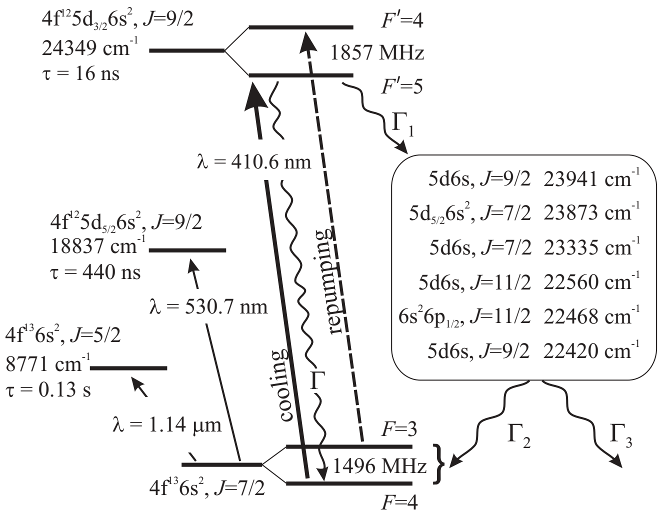


FIG. 1. Some relevant levels of atomic thulium. The transition $F = 4 \rightarrow F' = 5$ is used for the laser cooling, while the transition $F = 3 \rightarrow F' = 4$ is used for the repumping (optionally). The parameters $\Gamma$ and $\Gamma_{1,2,3}$ denote the corresponding decay rates.

The atomic beam is formed by two cylindrical diaphragms: D1 (3 mm in diameter, 2 cm long) and D2 (5 mm in diameter, 1 cm long). In the previous experiments [26] the flow of slowed atoms at the MOT position was measured to be $10^7$ s$^{-1}$ cm$^{-2}$ at a total flow of $10^9$ s$^{-1}$ cm$^{-2}$. The beam cross section is 1 cm$^2$ in the trapping region [26].

Atoms are cooled by the second harmonic of a Ti:sapphire laser at 410.6 nm. The laser frequency is stabilized to the Tm saturation absorption signal from the separate oven 2. The second oven is a continuously pumped stainless steel tube with Tm chunks inside which is heated to 900 K [19,26]. The acousto-optical modulator (AOM1) in a double-pass configuration shifts the laser frequency by a fixed red detuning of 400 MHz with respect to the cooling transition.

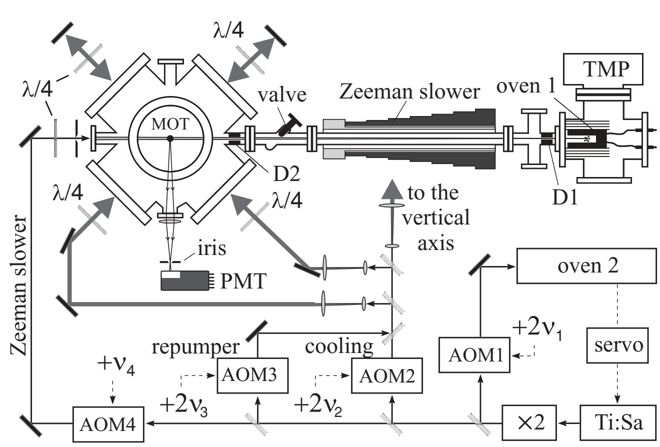


FIG. 2. The experimental setup. PMT denotes a photomultiplier tube; TMP denotes a turbo-molecular pump. The six-beam cross is pumped by an ion-getter pump (not shown). The AOMs 1,2,3 are working in a double-pass configuration at the frequencies $\nu_1 = 200$ MHz, $\nu_2 = 190 \div 200$ MHz, $\nu_3 = 300 \div 400$ MHz, while the AOM4 is working at single pass at $\nu_4 = 250$ MHz.

Up to 20 mW of the 410.6 nm power is sent to the second AOM (AOM2), also working in the double-pass configuration at around 200 MHz. This produces the cooling beam with the desired red detuning which is then split in three nearly round Gaussian shape beams of equal intensity, each expanded by a separate telescope to a diameter of 5 mm (at the $1/e$ level). A small fraction of power is sent to the third AOM (AOM3) which shifts the frequency into resonance with the $F = 3 \rightarrow F' = 4$ transition for repumping the atomic population from the $F = 3$ sublevel.

The fourth single-pass AOM (AOM4) works in the +1 order to produce the red-detuned frequency for the Zeeman slower. The frequency detuning, the light power, and the currents flowing through the Zeeman slower are optimized using the MOT luminescence signal. The number of trapped atoms monotonically grows with the increase on the light power sent to the slower. The maximal number of atoms is observed for the highest available power of the Zeeman slower light (typically 15 mW) and its red detuning of 150 MHz. At such detuning the Zeeman slower beam virtually does not interact with trapped atoms. The slowing light tuned to the resonance with the cooling transition also transfers the population from the $F = 3$ sublevel to the cooling cycle due to the off-resonance excitation (the corresponding rate is about $10^5$ s$^{-1}$) thus playing the role of the repumping laser in the atomic beam [10,26].

A fully loaded MOT has a typical size of 0.13 mm in diameter (at the $1/e$ level) which is measured by a charge-coupled device (CCD). In all other experiments the CCD was replaced by an absolutely calibrated photomultiplying tube (PMT) working in the current measurement regime. The MOT luminescence at 410.6 nm is collected by a lens and is focused onto the plane of the photocathode. An iris diaphragm of 3 mm in diameter is placed in the image plane for temperature measurements. The MOT image is adjusted to the iris center.

The temperature of the atoms in the MOT is measured by the release and recapture method described, e.g., in [27,28]. The slower and the MOT beams are simultaneously switched off, releasing atoms from the MOT. The MOT beams are switched on again after a certain time interval which was varied in steps from 1 to 30 ms. We measure the fraction of atoms left in the registration area. This fraction is defined by the size of the iris diaphragm and the atomic thermal velocity. For a red detuning of $\gamma$ and an intensity at the center of each beam $I_0 = 2$ mW/cm$^2$ the measured temperature equals 0.8(2) mK. This temperature is consistent with the evaluation obtained from the Doppler theory of optical molasses [27] which gives 1 mK for our experimental parameters. The equipartition theorem [29] gives a similar result for the measured MOT size. The Doppler cooling limit for the transition at 410.6 nm is $T_D = 0.23$ mK. Lower temperatures may be achieved by switching to another weaker cooling transition at 530.7 nm [19] (see Fig. 1).

To measure the lifetime of atoms in the MOT, the slower beam is promptly switched off by the AOM4. The loading process instantly stops and a luminescence signal of the decaying MOT is recorded by the PMT. After a complete decay of the MOT signal, the slower beam is switched on again and the loading curve is recorded. The quadrupole magnetic field of the MOT is left on.

Comparison of the decay and the loading curves allows us to evaluate the upper limit for the Tm-Tm binary collisions rate

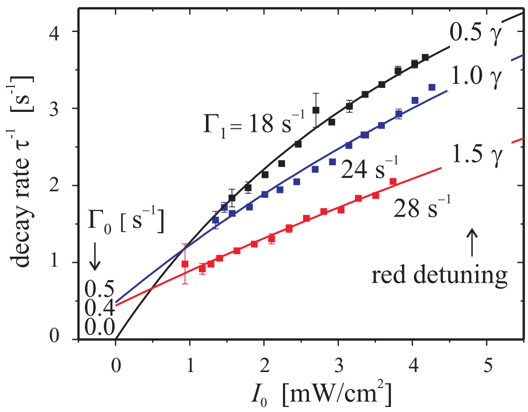


FIG. 3. (Color online) The decay time of the trapped atom number measured for different intensities and detunings of the cooling beams. Squares show the experimental data obtained for the red detunings of $0.5\gamma$ (black), $\gamma$(blue), and $1.5\gamma$ (red). $I_0$ is the intensity on the axis of each of the six MOT beams. Parameters $\Gamma_0$, $\Gamma_1$ correspond to the fits described in the text. The repumping laser is off.

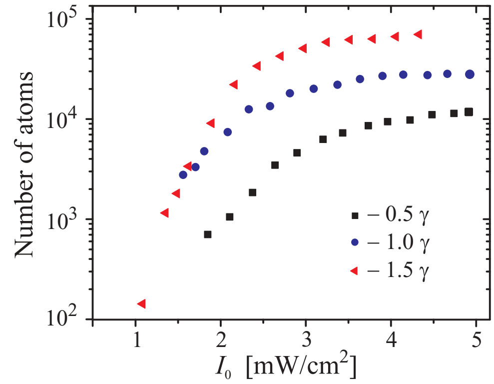


FIG. 4. (Color online) The number of atoms in the MOT for different powers and red detunings of the MOT beams. $I_0$ is the intensity on axis of each of the six beams.

constant which enters the corresponding nonlinear decay and loading MOT equations. From this evaluation we obtain the limit of $3(2) \times 10^{-10}$ cm$^3$ s$^{-1}$. Neglecting the binary collisions and using the single exponential fit to deduce the lifetime $\tau$ of atoms in the MOT leads to only 10% error for $\tau$. For further analysis we use the single exponential decay, adding 10% uncertainty to the error budget.

Decay curves do not show any clear observation of magnetically trapped atoms, as was demonstrated in [10,14]. Such a result may be accounted for the insufficient number of magnetically trapped Tm atoms due to their smaller magnetic moment compared to Er or Dy.

The measured MOT decay rate $\tau^{-1}$ for different on-axis intensities, $I_0$ (given per beam), and detunings of the cooling beams is shown in Fig. 3. Reduction of the lifetime at higher intensity results from the optical leaks to the six odd-parity levels shown in Fig. 1. Collisions with atoms from the beam do not significantly influence the lifetime. It is tested at the intensities of $I_0 > 3$ mW/cm$^2$ by partially closing the valve (installed right after the slower, Fig. 2) in such way that direct collisions with atoms from the beam are suppressed. In that case we observe a threefold reduction of the number of atoms in the MOT, but the lifetime in the MOT remains unchanged.

The complexity of configurations and a big number of intermediate levels impede detailed theoretical analysis of the system. Here we consider the simplest model of two cooling levels coupled with the laser field with a decay channel from the upper level. We assume that no population leaked from the cooling cycle returns back via cascade decays to the ground state ($\Gamma_2 = 0$). As experiments with the repumping laser indicate the model is incomplete (see further), but it provides the lower limit for the decay rate $\Gamma_1$. The extension of the model to a more realistic situation (similar to that shown in Fig. 1) gives ambiguous results due to the lack of experimental data.

The solution to the equations describing our model gives

$$\tau^{-1} = \Gamma_0 + \Gamma_1 R/(1 + R), \tag{1}$$

where parameter $\Gamma_0$ stands for losses independent of the light intensity, e.g., collisions with a background gas. The parameter $R$ is given by $R = S/(1 + S + 4\kappa^2)$, where $\kappa$ is the detuning in units of $\gamma$ and $S = 6I_0/I_{sat}$ is the saturation parameter ($I_{sat} = 2\pi^2 hc\gamma/3\lambda^3 = 19$ mW/cm$^2$).

The curves obtained by fitting (1) to the data as well as the best fit parameters $\Gamma_0$ and $\Gamma_1$ are shown in Fig. 3. The decay rate $\Gamma_1$ grows with the increasing red detuning, which is probably due to the incompleteness of the model. The lifetime extrapolated to zero intensity $I_0 = 0$ is about $\Gamma_0^{-1} \simeq 2$ s for the red detunings of $\gamma$ and $1.5\gamma$. It is mostly caused by collisions with the background gas and is typical for other MOTs observed at similar vacuum conditions. For the detuning of $0.5\gamma$ the transition is more strongly saturated and the extrapolation to zero intensity may result in a bigger error for a given model. Moreover, at this detuning the MOT becomes very sensitive to the laser lock quality. We conclude that the lower limit for the decay rate from the level $4f^{12}5d6s^2(J' = 9/2)$ equals 22(6) s$^{-1}$. It is consistent with the previous theoretical estimation predicting a rate between 300 and 1200 s$^{-1}$ [19].

The number of atoms trapped in the MOT for different detunings and powers of the cooling beams is shown in Fig. 4. The maximal number of atoms observed in our experiments corresponds to $7 \times 10^4$ for higher Zeeman slower and cooling beam power and the number rapidly decreases for lower powers. The oven 1 temperature strongly influences the number of atoms which indicates that the number of atoms in the MOT is far from the saturation. An increase of the oven temperature by 50 K results in an approximately twofold increase of the signal. We deliberately did not increase the temperature to avoid coating the Zeeman slower window. The number of atoms may be further increased by implementation of the "dark" MOT [30]. Because of the dominating role of optical leaks in the Tm MOT, the configuration of the dark MOT proposed in [30] should be modified in such way that all six cooling beams should have a hole at their centers.

The presence of a repumping laser tuned into exact resonance between $F = 3$ and $F' = 4$ hyperfine sublevels (Fig. 1) increases the lifetime $\tau$ and the number of atoms

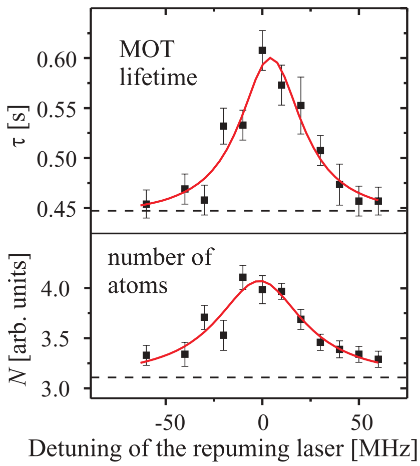


FIG. 5. (Color online) The MOT lifetime $\tau$ and the number of atoms $N$ vs the repumping laser detuning from the $F = 3 \rightarrow F' = 4$ resonance. The repumping beam intensity equals 2 $\mu$W/cm$^2$ at the MOT position. The MOT beams red detuning is $\gamma$, $I_0 = 3$ mW/cm$^2$. Solid curves are the Lorentzian fits. Dashed lines denote corresponding values measured in the absence of the repumping laser.

$N$ in the MOT by about 30% for a given set of experimental conditions (see Fig. 5). A comparison of Figs. 5 and 3 shows that the repumping laser does not completely close optical leaks, since the MOT lifetime does not reach the extrapolated value of $\Gamma_0^{-1}$.

This result indicates that a part of the population leaked from the cooling cycle returns back to the ground state via further decays. Such a refilling channel ($\Gamma_2 \neq 0$) is not taken into account in the model (1) which can explain some peculiarities of the fit in Fig. 3. Unfortunately, the insufficient number of observable parameters does not allow for qualitative characterization of $\Gamma_2$. The repumping laser intensity of about 2 $\mu$ W/cm$^2$ is enough to close the corresponding leak channel: Fig. 5 corresponds to the saturated regime since the spectral width of the fits is approximately four times broader than the natural linewidth.

In conclusion, we have demonstrated laser cooling and trapping of up to $7 \times 10^4$ thulium atoms at 0.8(2) mK in a magneto-optical trap working at 410.6 nm. Measurement of the lifetime in the MOT gives a lower limit for the decay from the upper cooling level $4f^{12}5d6s^2(J' = 9/2)$ of 22(6) s$^{-1}$. The repumping laser is not obligatory, but increases the lifetime and number of atoms in the MOT.

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