Magneto-Optical Trap for Thulium Atoms

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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 MOT which varies between 0.3 - 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.

PACS numbers: 37.10.Gh, 37.10.De, 32.30.Jc

Laser cooling and trapping of neutral atoms is one of the most powerful tools to study atomic ensembles at ultra-low 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]. These new cold species find applications in metrology, quantum information, tests of fundamental theories, and degenerate gas studies.

First, their ground state magnetic moment is much larger than that of the alkalis. 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 $4f^{10}6s^2$ 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 $4f^{10}6s^2$ consists of two sublevels with the total electronic momentum quantum numbers $J = 7/2$ and $5/2$. This sublevels are optically coupled by a narrow (width of $1.2(4)$ Hz [19]) magnetic dipole transition at 1.14 $\mu$m (fig 1). The upper sublevel being a long-live 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 reducing of a 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]. Theoretical analysis of the leak rates from the cooling cycle indicated that the most favorable for the first cooling step is $4f^{10}6s^2 (J = 7/2, F = 4) \rightarrow 4f^{12}5d6s^2 (J' = 9/2, F' = 5)$ transition at 410.6 nm with the natural line width of $\gamma = \Gamma/2\pi = 10(4)$ MHz, where small and capital letters denote rates in Hz and cycles 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 using laser radiation at 410.6 nm without a repumping laser [24]. 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 anti-propagating cooling laser beams as shown in fig. 2. The MOT chamber is a 6-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 home-made 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.

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 [24] the flow of slowed atoms at the MOT position was measured to be $10^7$ s$^{-1}$ cm$^{-2}$ at a total flow (rate) of $10^9$ s$^{-1}$ cm$^{-2}$. The beam cross-section is 1 cm$^2$ in the trapping region [24].

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.

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 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 Zeeman slower are optimized using the MOT luminescence signal. The maximal number of trapped atoms is observed for a red detuning of 150 MHz and the highest available light power (typically about 15 mW). 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 a 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 1/e level) which is measured by a charge-coupled device (CCD). In all other experiments the CCD was replaced by an absolutely calibrated photo-multiplying 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. A 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 ms 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 $I_0 = 2 \text{ mW/cm}^2$ the measured temperature equals 0.8(2) K. This temperature is consistent with the evaluation obtained from the Doppler theory of optical molasses [27] which gives 1 mK for our experimental parameters. Equi-partition theorem [29] gives a similar result for the measured MOT size. The Doppler cooling limit for the transition at 410.6 nm is $T_D = 0.23 \text{ mK}$. Lower temperatures may be achieved by switching to another weaker cooling transition at 530.7 nm [19] (see fig. 11).

After the MOT beams are switched on again a quick (~10 ms) recapture process takes place which is followed by the

![FIG. 2: The experimental setup. The PMT denotes a photomultiplier tube, the TMP – a turbo-molecular pump. The 6-cross is pumped by a ion-getter pump (not shown). The AOMs 1, 2, 3 are working in a double-pass configuration at the frequencies $\nu_1 = 200 \text{ MHz}$, $\nu_2 = 190 \div 200 \text{ MHz}$, $\nu_3 = 300 \div 400 \text{ MHz}$, while the AOM4 is working at single pass at $\nu_4 = 250 \text{ MHz}$.](image)
decay of the signal due to the trap losses. We observe a single exponential decay with no indication of magnetically trapped atoms or refilling of the cooling cycle from the corresponding population reservoir, as was measured for erbium \[10\]. The MOT is reloaded in 3 seconds by switching on the slower light beam (the steady-state MOT luminescence is not detectable in its absence).

The lifetime of atoms in the MOT, $\tau$, is measured from the decay curves by fitting an exponential to the experimental data. At our atom number density of $10^{11}$ cm$^{-3}$ the role of binary collisions is negligible and the MOT is optically thin which justifies the use of an exponential decay fit. We observe no systematic difference between the lifetimes deduced from the decay curves and from the loading curves. At high intensities of the MOT beams ($I_0 > 3$ mW/cm$^2$, see fig. 3) collisions with atoms from the beam also play insignificant role. It was tested by closing partially the valve (installed right after the slower, fig. 2) such way, that direct collisions with atoms from the beam are suppressed. In that case we observed three-fold reduction of the number of atoms, but the lifetime in the MOT remained unchanged.

Results for different on-axis intensities, $I_0$ (given per beam), and detunings of the cooling beams are shown in fig. 4. Reduction of the life time at higher intensity results from the optical leaks to the six odd-parity levels shown in fig. 1. 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

$$\tau^{-1} = \Gamma_0 + \Gamma_1 R/(1 + R),$$  \hspace{1cm} (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 $S = I_0/I_{sat}$ is the saturation parameter ($I_{sat} = 0.1$ 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 parameter $\Gamma_0$ obtained for the detunings of $\gamma$ and $1.5 \gamma$ corresponds to a MOT lifetime of about 1.5 s which 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 s$^{-1}$ 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 two-fold 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 \[30\].

A presence of repumping laser tuned into exact resonance between $F = 3$ and $F' = 4$ hyperfine sublevels (fig 1) increases the life time $\tau$ and the number of atoms $N$ in the MOT by about 30% for a given set of experimental conditions (see fig. 5). This result indicates that a part of 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 1 $\mu$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 4 times broader than the natural
In conclusion, we have demonstrated laser cooling and trapping of up to $7 \times 10^4$ thulium atoms at 0.8(2) K 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 $4^f_{12}5d_{6s}^2 (J' = 9/2)$ of 22(6) s$^{-1}$. The repumper laser is not obligatory, but increases the lifetime and number of atoms in the MOT.

The work is supported by the RFBR grant 09-02-00649, Presidential grant MD-3825.2009.2 and RSSF.

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