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# Measurement of the upper clock level lifetime in $^{169}\text{Tm}$

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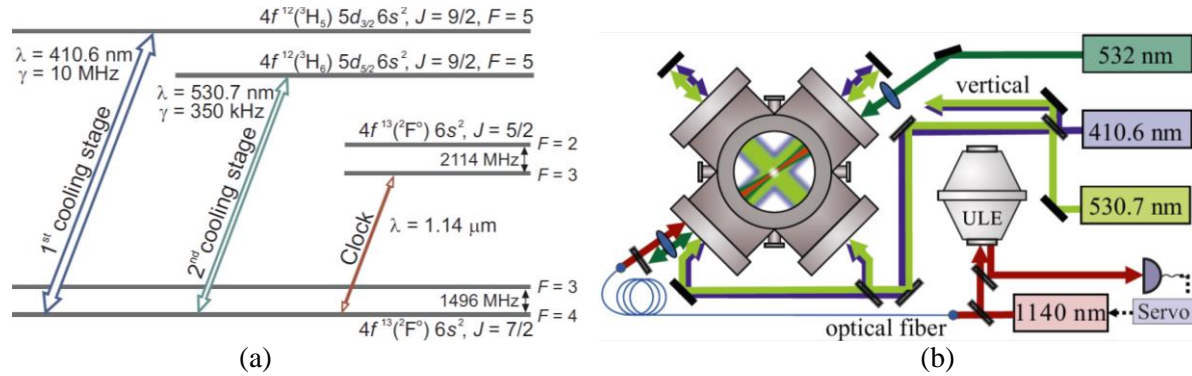
**Abstract.** We determine a lifetime of the  $4f^{13}6s^2$  ( $J = 5/2$ ) clock level in  $^{169}\text{Tm}$  atoms trapped in an optical lattice at 532 nm directly exciting a  $1.14\ \mu\text{m}$  magneto-dipole transition and measuring a decay rate from this level to the ground ( $J = 7/2$ ) state. The measured lifetime of 112(4) ms corresponds to a transition spectral line width of 1.4 Hz which is in a good agreement with a theoretical prediction of 1.14 Hz.

## 1. Introduction

Precise timekeeping is an important technology for industry and science. The realization of the optical lattice clocks brings the fractional instability to the  $10^{-18}$  range [1, 2], and enables new fundamental research, like testing a drift of the fundamental constants [3, 4] and probing the general relativity [5]. The main limiting factor in optical clocks is the clock transition shift caused by the black body radiation (BBR) [6, 7, 8]. Magneto-dipole transitions between fine-structure states of the lanthanides correspond to flipping of spin of the unpaired electrons in the submerged  $4f$  electron shell. This shell is shielded from an external electric field by the outer  $5s^2$  and  $6s^2$  shells [9]. This shielding results in a small BBR shift of these magneto-dipole transitions and renders them as promising candidates for new optical clocks [10, 11].

Thulium is a lanthanide with one vacancy in the inner  $4f$  electron shell. Similar to other lanthanides [12, 13, 13, 14], laser cooling of Tm is achieved in two stages. The first-stage cooling is done at a strong 410.6 nm transition which routinely allows reaching a sub-Doppler temperature of 80  $\mu\text{K}$  in a cloud of  $2 \times 10^6$  atoms [15]. The second cooling stage at a weak 530.7 nm transition results in a Doppler-limited temperature of 9  $\mu\text{K}$  [16]. This temperature is low enough to load atoms in a shallow optical trap or a lattice using 532 nm laser radiation [17]. Relevant Tm levels are shown in Fig. 1a.





**Figure 1.** (a) Relevant energy levels of  $^{169}\text{Tm}$ . The strong transition at 410.6 nm is used for the first-stage laser cooling, and detecting the ground state populations and the weak transition at 530.7 nm is used for the second-stage cooling. The proposed clock transition  $4f^{13}6s^2 (J = 7/2, F = 4) \rightarrow 4f^{13}6s^2 (J = 5/2, F = 3)$  is at the wavelength of 1.14 μm.

(b) A Schematic diagram of the experimental setup: blue and light green lines are the cooling beams with 410.6 nm and 530.7 nm wavelength, respectively, dark green is optical lattice beam. 1.14 μm laser is stabilized to a high-finesse ULE cavity and is guided to the MOT region via optical fiber.

In this paper, we present measurement of the upper  $|J = 5/2\rangle$  clock level lifetime of Tm atoms trapped in the optical lattice at 532 nm. We also show that after loading atoms to the optical lattice only a small fraction of atoms are in the  $|m_F = 0\rangle$  and additional pumping is required.

## 2. Lifetime of the $|J = 5/2\rangle$ clock level

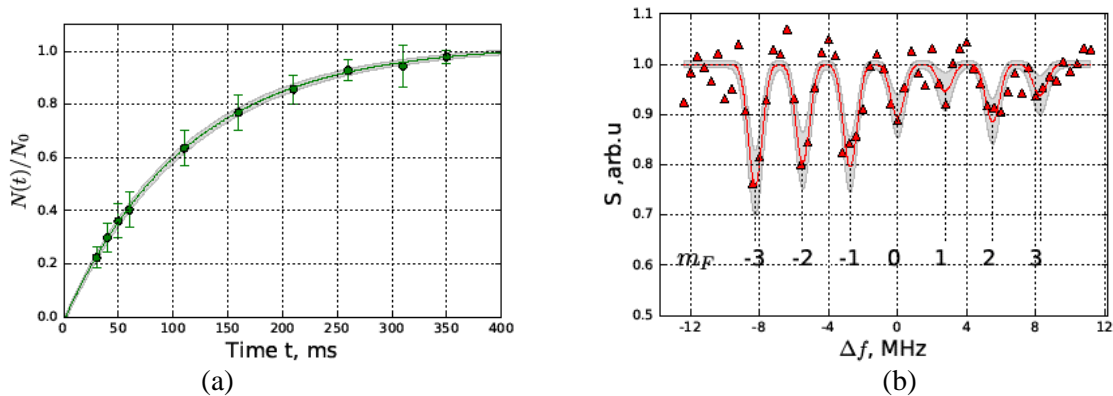
The lifetime of the  $|J = 5/2\rangle$  clock level is measured by excitation of the magnetic dipole transition at 1.14 μm in a 1D optical lattice. An experimental setup is shown in Fig. 1b and described elsewhere [16, 17]. About 106 thulium atoms are laser cooled down to 20 μK in a narrow-line magneto-optical trap (MOT) operating at 530.7 nm and then are recaptured by the 1D optical lattice. The lattice is formed by a retro-reflected focused 532nm cw laser beam (waist radius is 50 μm, laser power is 3W) and superimposed with the atomic cloud. The trap depth is calculated to be 400 μK for the ground  $|J = 7/2, F = 4\rangle$  state which together with good spatial overlapping provides a recapture efficiency of 40%.

After recapture, we switch the MOT off and wait for 20 ms to let uncaptured atoms escape. Then, we excite atoms to the  $|J = 5/2, F = 3\rangle$  level applying a resonant 1.14 μm laser pulse for 30 ms [18]. The laser is actively stabilized to a high-finesse ultralow expansion (ULE) cavity [19] which narrows the laser spectral line width down to ~10 Hz. After the interrogation pulse, a resonant 410.6 nm laser pulse of 1 ms is applied to remove atoms from the  $|J = 7/2\rangle$  ground state (Fig. 1a). Atoms excited to the  $|J = 5/2, F = 3\rangle$  decay back to the  $|J = 7/2, F = 4\rangle$  ground state, which population is monitored by means of a fluorescence induced by a delayed 410.6 nm probe pulse.

The increase of the population of the  $|J = 7/2, F = 4\rangle$  ground state is described by the exponential function

$$N(t) = N_0 (1 - \exp(-t/\tau)), \quad (1)$$

where  $\tau$  is the lifetime of the excited  $|J = 5/2, F = 3\rangle$  state and  $N_0$  is a total number of atoms returned to the ground state. By fitting the experimental data presented in Fig. 2a, we measure  $\tau = 112(4)$  ms. It is the lower bound for the  $|J = 5/2\rangle$  level natural lifetime since the measured lifetime can be reduced by additional weak losses from the  $|J = 5/2\rangle$  level in the optical lattice. Thus, the natural line width of the clock transition  $|J = 7/2\rangle \rightarrow |J = 5/2\rangle$  is not broader than 1.4 Hz and is consistent with a previous measurement in  $^4\text{He}$  matrix [20] and a theoretical prediction of 1.14 Hz [21].



**Figure 2.** (a) Measurement of the lifetime of the  $|J = 5/2\rangle$  level. Dots are the normalized number of atoms decayed to the ground  $|J = 7/2, F = 4\rangle$  level averaged over 9 series of measurements. A solid curve is a fit by (1) with a statistical  $1\sigma$  standard deviation shown as gray area.

(b) Normalized Zeeman spectrum of  $|J = 7/2, F = 4\rangle \rightarrow |J = 5/2, F = 3\rangle$  transition in  $\pi$ -polarized  $1.14 \mu\text{m}$  radiation.  $\Delta f$  is probe beam frequency detuning from  $|m_F = 0\rangle \rightarrow |m_F = 0\rangle$  transition,  $S$  is normalized number of atoms remained in the  $|J = 7/2, F = 4\rangle$  ground state after excitation by 30 ms probe pulse at  $1.14 \mu\text{m}$ . Experimental data (triangles) are fitted with a sum of equidistantly separated Gaussian functions with equal widths (solid line). Gray area shows statistical  $1\sigma$  standard deviation of the fit.

### 3. Ground state magnetic sublevels population distribution

To minimize sensitivity of the  $|J = 7/2, F = 4\rangle \rightarrow |J = 5/2, F = 3\rangle$  clock transition frequency to interatomic dipole-dipole interaction, vector Stark shift, and linear Zeeman shift we plan to interrogate  $|m_F = 0\rangle \rightarrow |m_F = 0\rangle$  of its Zeeman manifold transition in future Tm optical frequency standard [10]. To improve signal-to-noise ratio and to decrease systematic errors, atomic ensemble should be prepared in the  $|m_F = 0\rangle$  state. In Fig. 2b we show spectrum of the  $1.14 \mu\text{m}$  transition under applied an external magnetic field  $B_0 = 6.6 \text{ Gs}$  in a  $\pi$ -polarized probe light where 7 transitions with  $m_F$  from -3 to +3 are clearly distinguishable. There are no  $\pi$ -transitions from  $m_F = -4$  or  $m_F = 4$  to upper  $|J = 5/2, F = 3\rangle$  level. A spectral line width of the individual transition is approximately  $0.55 \text{ MHz}$  and is close to expected inhomogeneous power broadening of  $\sim 0.4 \text{ MHz}$  caused by different dynamic polarizabilities of the  $|J = 7/2, F = 4\rangle$  and  $|J = 5/2, F = 3\rangle$  levels at  $532 \text{ nm}$ . Taking into account populations of  $m_F = -4$  and  $m_F = 4$  sublevels we estimate that only about 10% of all atoms in the optical lattice are in the  $|m_F = 0\rangle$  state. Required optical pumping to the  $|F = 4, m_F = 0\rangle$  sublevel can be performed using a  $\pi$ -polarized light resonant with a  $|J = 7/2, F = 4\rangle \rightarrow |J = 9/2, F = 4\rangle$  transition at  $410.6 \text{ nm}$  since the  $|F = 4, m_F = 0\rangle$  state is a dark state in this configuration [22, 23].

In conclusion, we measured the lifetime of the upper clock level  $4f^{43}6s^2$  ( $J = 7/2$ ) of Tm in the 1D optical lattice at  $532 \text{ nm}$  to be  $112(4) \text{ ms}$  which sets the upper limit to a natural spectral linewidth of  $1.4 \text{ Hz}$  of the magneto-dipole transition  $|J = 7/2, F = 4\rangle \rightarrow |J = 5/2, F = 3\rangle$ . Optical pumping to the  $|F = 4, m_F = 0\rangle$  state is required since only a small fraction of atoms in optical lattice is initially in the  $|m_F = 0\rangle$  state. Finally, narrow line width and small sensitivity to BBR shift [10] of the  $|J = 7/2, F = 4\rangle \rightarrow |J = 5/2, F = 3\rangle$  transition as well as simple experimental scheme make the Tm atom a promising candidate for optical frequency standards.

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## References

- [1] Bloom B J, Nicholson T L et al. 2014 *Nature* **506** pp 71-5.
- [2] Hinkley N, Sherman J A et al. 2013 *Science* **341** pp 1215-8.
- [3] Rosenband T, Hume D et al. 2008 *Science* **319** pp 1808-12.
- [4] Kolachevsky N N 2008 *Physics-Uspekhi* **51** pp 1180-90.
- [5] Chou C W, Hume D et al. 2010 *Science* **329** pp 1630-3.
- [6] Beloy K, Hinkley N et al., 2014 *Physical Review Letters* **113** p 260801.
- [7] Safronova M S, Porsev S G et al. 2013 *Physical Review A* **87** p 012509.
- [8] Ushijima I, Takamoto M et al. 2015 *Nature Photonics* **9** pp 185-9.
- [9] Aleksandrov E, Kotylev V et al. 1983 *Opt. Spektrosc.* **54** p 3.
- [10] Sukachev D, Fedorov S et al. 2016 *Physical Review A* **94** p 022512.
- [11] Kozlov A, Dzuba V et al. 2013 *Physical Review A* **88** p 032509.
- [12] Aikawa K, Frisch A et al. 2012 *Physical Review Letters* **108** p 210401.
- [13] Lu M, Burdick N Q et al. 2011 *Physical Review Letters* **107** p 190401.
- [14] Miao J, Hostetter J et al. 2014 *Physical Review A* **89** p 041401.
- [15] Sukachev D, Sokolov A et al. 2010 *Physical Review A* **82**.
- [16] Vishnyakova G A, Golovizin A A et al. 2016 *Physics-Uspekhi* **59** p168.
- [17] Sukachev D D, Kalganova E S et al. 2014 *Quantum Electronics* **44** pp 515-20.
- [18] Golovizin A A, Kalganova E S et al. 2015 *Quantum Electronics* **45** pp 482-5.
- [19] Alnis J, Matveev A et al. 2008 *Physical Review A* **77** p 053809.
- [20] Ishikawa K, Hatakeyama A et al., 1997 *Physical Review B* **56** pp 780-7.
- [21] Kolachevsky N N, Akimov A V et al. 2007 *Applied Physics B* **89** pp 589-94.
- [22] Magunov A I and Palchikov V G 2014 *Journal of Exper. and Theor. Physics* **118** pp 687-700.
- [23] Martin J, Shore B W et al. 1996 *Physical Review A* **54** pp 1556-69.