Systematic Frequency Shifts in Bi-color Tm Optical Clock

K. Khabarova, A. Golovizin, D. Tregubov, E. Fedorova, D. Mishin, D. Provorchenko, V. Sorokin, N. Kolachevsky
P.N. Lebedev Physical Institute
Moscow, Russia
habarovaky@lebedev.ru

K. Khabarova, N. Kolachevsky
Russian Quantum Center
Moscow, Russia

***Abstract*—The 1.14 μm inner-shell magnetic dipole transition in neutral thulium possesses very low blackbody radiation shift in comparison to other neutrals. Together with other features of Tm electronic structure it opens new perspectives for compact optical clocks almost free from hard-to-control systematic shifts.**

Keywords—Thulium; optical clock; black body radiation shift; bi-color interrogation; magic wavelength

I. Introduction

Although optical atomic clocks have overcome the eighteenth decimal digit of instability and uncertainty demonstrating incredible control over external perturbations of the clock transition frequency [1] most of them remain difficult-to-maintain laboratory setups. There is an increasing demand for atomic and ionic transitions with minimal sensitivity to external fields, with practical operational wavelengths and robust readout protocols. One of the goals is to simplify clock's operation maintaining its relative uncertainty at the low 10^{-18} level.

Largest systematic shifts in lattice clocks come from the lattice and interrogation light fields, blackbody radiation (BBR) and an external magnetic field (the Zeeman shift) [2].

Here we show that for thulium based optical clock all major frequency shifts can be controlled at the 10^{-18} level. Together with low sensitivity to collisions and black body radiation (BBR) it makes thulium a promising candidate for a transportable room-temperature optical atomic clock due to soft constraints on the ambient temperature stability. It combines advantages of unprecedented frequency stability of optical lattice clocks based on neutral atoms and low sensitivity to BBR of ion optical clocks.

II. Results

a) Stark shifts. Specific shielding of the inner 4f-shell magnetic-dipole clock transition at the wavelength of 1.14 μm in Tm by outer $5s^2$ and $6s^2$ electronic shells results in a very low sensitivity of its frequency to external electric fields. Earlier we've theoretically shown that this fact should result in low sensitivity of the clock transition in Tm to collisions and BBR [3].

Using direct laser spectroscopy we measured differential polarizabilities of the clock levels in Tm at wavelengths in the

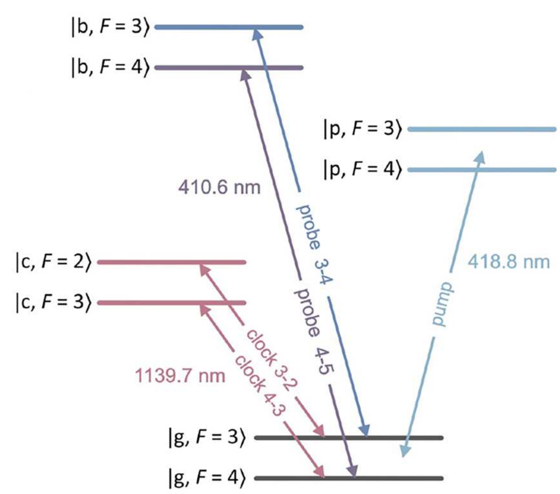

Fig.1 Energy levels and relevant transitions for neutral Tm.

range 810-860 nm and at 1064 nm and infer the static scalar differential polarizability of the inner-shell clock transition of 0.063(30) atomic units corresponding to only $2.3(1.1)\times10^{-18}$ fractional frequency shift from BBR at room temperature. This is a few orders of magnitude smaller compared to the BBR shift of the clock transitions in neutral atoms (Sr, Yb, Hg) and competes with the least sensitive ion species (e.g. Al^+ or Lu^+). For the 1.14 μm clock transition, we experimentally determined the "magic" wavelength of 813.320(6) nm, recorded a transition spectral linewidth of 10 Hz, and measured its absolute frequency of 262 954 938 269 213(30) Hz [4].

Clock transition frequency shift from the optical lattice electric field has the leading term:

$$h\Delta\nu = -\Delta\alpha E^2/4. \quad (1)$$

978-1-6654-3935-0/21/$31.00 ©2021 IEEE

Here E is the amplitude of the electric field and Δα is a differential polarizability of the clock levels, which for mF = 0 -> mF = 0 transitions can be written as:

$$\Delta\alpha = \Delta\alpha^s + \frac{3\cos^2\Theta - 1}{2}\Delta\alpha^t, \qquad (2)$$

where $\Delta\alpha^s$ and $\Delta\alpha^t$ are scalar and tensor differential polarizability of the clock levels respectively. Θ is the angle between the quantization axis (the direction of the external magnetic field B) and the electric field polarization of the optical lattice. As one can see from (2) the contribution to the frequency shift of the tensor polarizability depends on the angle Θ. Although one needs to control (and ideally stabilize) this angle during clock operation, variable contribution from the tensor part of polarizability leads to a wider choice of the magic wavelengths owing to very small differential scalar polarizability in IR region. Particularly, there is another magic wavelength near 1064 nm at Θ=π/2 (Fig.2). Due to the fact, that the slope of the differential polarizability curve around 1064 nm is small the requirements for the frequency stability of the lattice laser are reduced and can be easily met using commercially available fiber lasers and frequency stabilization to i.e. wavemeter.

Yet the advantages of the 4f-shell clock transition come with a price: asymmetric structure of the electron wave function and the strong magnetic dipole-dipole interaction. The asymmetry of the wave function results in nonzero tensor polarizability, which should be taken into account as mentioned above. The contribution from the dipole-dipole interaction can be cancelled out by use of transition between zero projections of total atomic momentum $m_F = 0$ -> $m_F = 0$, which is the case for the atoms with integer value of the total atomic moment F. At the same time for $m_F = 0$ states the linear Zeeman shift is zero.

As we've shown in [5] Tm atoms can be effectively pumped to the $m_F = 0$ magnetic sublevel of the ground state through the $|J = 7/2, F = 4\rangle$ $|J' = 9/2, F' = 4\rangle$ transition with π-polarized light at λ=530.7 nm which is used for the second stage cooling. Here no additional laser source is required although it is necessary to use not only a pumping but also a repumping laser beam. Large number of scattered photons can cause heating and losses of the atoms from the trap. To avoid this we choose another transition between levels with the equal total atomic momentum F and total electron momentum J. In this case, no repumper is needed and during the pumping procedure at 418.8 nm transition both hyperfine sublevels of the ground state are populated with 36% and 4% of initial number of atoms [6].

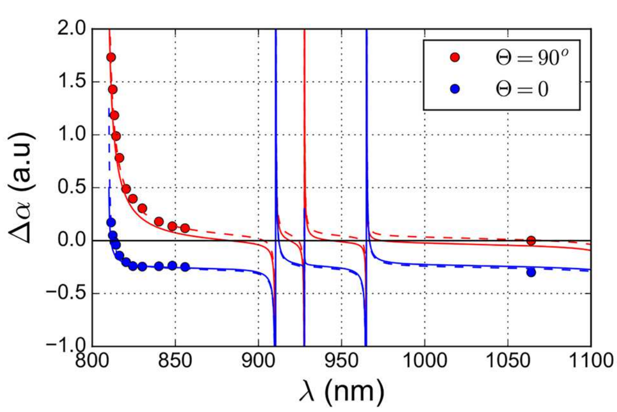

Fig.2 Differential polarizabilities of the clock levels at two angles Θ between the quantization axis and the electric field polarization of the optical lattice.

The key systematic contribution to the frequency shift of the 1.14 μm clock transition is the second order Zeeman shift of 257 Hz/G^2. Handling this shift and angle-dependent lattice light simultaneously requires unconventional approach because of their opposite behavior with respect to the bias magnetic field B_0.

Simultaneous population of the hyperfine components of the ground state appeared to be a lucky feature of the pumping procedure at 418.8 nm transition. It allows to simultaneously probe two clock transitions $|g, F = 4, m_F = 0\rangle \rightarrow |c, F = 3, m_F = 0\rangle$ ("4-3") and $|g, F = 3, m_F = 0\rangle \rightarrow |c, F = 2, m_F = 0\rangle$ ("3-2") (Fig.1) which have equal but opposite Zeeman shifts. As a result, for the synthetic frequency

$$\nu_s = \frac{\nu_{43} + \nu_{32}}{2} \qquad (3)$$

the Zeeman shift fully cancels without any assumptions concerning magnetic field behavior between consecutive measurements.

Nonzero differential tensor polarizability of the clock levels imposes strict requirements on the quantization axis alignment and the lattice light polarization purity. Control of |Θ| < 10−3 provides Δν < 1 mHz for a lattice depth of 100Er. Thus, the magnetic field (more precisely its component perpendicular to the lattice polarization) should be stabilized at a level of 10^{-3}B, or 0.1 mG for the bias field of 100 mG, which can be easily achieved with magnetic shielding or active stabilization of the B-field direction.

III. DISCUSSION

Here we report on main systematic frequency shifts in Tm optical lattice clock with bi-color clock interrogation scheme. The clock operates at 1.14 μm inner-shell magnetic dipole transition. Very low sensitivity of Tm clock transition to the BBR shift (2.3×10^{-18} at the room temperature) makes Tm optical lattice clock a promising system for outdoor applications. The operational magic wavelength around 1064

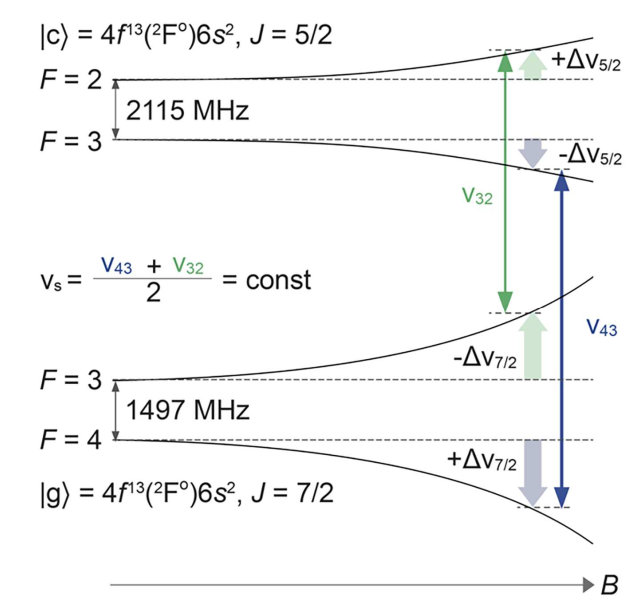

Fig. 3 Magnetic doublets of the ground- and excited-states clock levels. Two simultaneously interrogated transition frequencies are denoted as ν_{43} and ν_{32}.

nm provides further advantages in comparison with many others optical atomic clocks from the presence of powerful fiber lasers to more than 1000 times lower sensitivity to the lattice frequency stability. Simultaneous population of the hyperfine sublevels of the ground state and bi-color interrogation scheme of clock transition results in cancelation of the Zeeman shift contribution. Summing up, bi-color Tm optical clock operating at 1.14 μm inner-shell magnetic dipole transition demonstrates low overall systematic frequency shifts and requires very moderate environmental conditions. The list of main systematic effects with corresponding clock transition frequency shifts and uncertainties is presented in Table I.

TABLE I. SYSTEMATIC FREQUENCY SHIFTS AND UNCERTAINTIES OF THE THULIUM OPTICAL LATTICE CLOCK AT 1.14μM TRANSITION.

Source	**Shift, 10^{-18}**	**Uncertainty, 10^{-18}**	**Conditions**
BBR	2.3	1.1	T = 300±3 K, uncertainty from the uncertainty of $\Delta\alpha^s_{DC}$
Lattice, θ-dependent part	0	1	$\lvert\Delta\Theta\rvert < 10^{-3}$, U = 100Er
Lattice, higher-order shifts	<10	<10	Our current estimations based on the M1 polarizability from the 1.14 clock transition.
Quadratic Zeeman	<1	<1	B=200 mG, unknown residual quadratic coefficient.
Mutual influence of two clock transitions	0	<10 (?)	Simulations show no mutual influence, to be confirmed experimentally
Stray electric fields	0	<0.1	E < 1 V/cm, $\lvert\nabla E\rvert$ < 0.05 V/cm^2

I. CONCLUSIONS

Thulium atom electronic structure has several features that significantly simplify trapping, laser cooling and control of the atomic state. Despite the large magnetic moment and nonzero differential tensor polarizability, it is possible to obtain total frequency shift of the synthetic clock frequency and its uncertainty at the 10^{-18} level. Together with low sensitivity to BBR it makes the Tm optical lattice clock operating at 1.14 μm inner-shell magnetic dipole transition a perspective system for next generation of clocks suitable for outdoor maintaining.

ACKNOWLEDGMENT

The work was supported by the Russian Science Foundation (Grant No. 19-12-00137)

REFERENCES

[1] T. Bothwell et.al. "Sr optical lattice clock with uncertainty of 2.0·10 -18," Metrologia, vol. 56, pp. 065004, 2019.

[2] M. Takamoto et.al. "Test of general relativity by a pair of transportable optical lattice clocks." Nature Photonics, vol. 14(7), pp.411–415, 2020.

[3] D. Sukachev et al., Inner-shell magnetic dipole transition in Tm atoms: A candidate for optical lattice clocks", Phys. Rev. A. vol. 94, pp. 022512, 2016.

[4] Golovizin, A., et al. "Inner-shell clock transition in atomic thulium with a small blackbody radiation shift." Nature communications vol. 10(1) pp. 1-8, 2019 .

[5] Fedorova, E., et al. "Optical pumping of ultracold thulium atoms to a lower level of the clock transition and study of their depolarisation." Quantum Electronics vol. 49(5) pp. 418 2019.

[6] Fedorova, E., et al. "Simultaneous preparation of two initial clock states in a thulium optical clock." Physical Review A vol. 102(6), pp. 063114 2020.

.