$^{171}Yb^+$ Single-Ion Optical Frequency Standards

I. Sherstov, Chr. Tamm, B. Stein, B. Lipphardt, H. Schnatz, R. Wynands, S. Weyers, T. Schneider, E. Peik*
Physikalisch-Technische Bundesanstalt
38116 Braunschweig, Germany

* Present Address: Laboratoire Kastler Brossel, ENS, Paris, France

***Abstract*—We present work on a frequency standard based on the $^2S_{1/2}(F=0, m_F=0) \rightarrow {}^2D_{3/2}(F=2, m_F=0)$ electric quadrupole transition in $^{171}Yb^+$ at 688 THz, and future plans for a frequency standard based on the $^2S_{1/2}(F=0, m_F=0) \rightarrow {}^2F_{7/2}(F=3, m_F=0)$ electric octupole transition in the same ion at 642 THz. Direct measurement of the ratio of these two frequencies, derived from a single ytterbium ion, constitutes a sensitive test for the temporal constancy of the fine structure constant.**

A laser cooled $^{171}Yb^+$ ion in a radio-frequency trap is a nearly ideal reference for an optical frequency standard [1] and for a laboratory search for temporal variations of fundamental constants [2, 3]. For a number of single-ion optical frequency standards, one expects that systematic shifts of the atomic transition frequency can be reduced to the 10^{-18} range [4], which would improve by more than two orders of magnitude on the best available cesium fountains. Optical frequency conversion techniques based on femtosecond comb generators permit the realization of practical single-ion frequency standards with output frequencies in the optical and microwave range.

We have conducted absolute frequency measurements of the $^{171}Yb^+$ frequency standard based on the $^2S_{1/2}(F=0, m_F=0) \rightarrow {}^2D_{3/2}(F=2, m_F=0)$ electric quadrupole transition at 688 THz. In these measurements, the second harmonic of the probe laser frequency is stabilized to the reference transition of a trapped $^{171}Yb^+$ ion. A part of the 871 nm (344 THz) probe laser output is passed through an 8 m fiber link to produce a beat signal with the frequency-doubled output of an Er^{3+}-doped fiber frequency comb generator [5]. The comb generator is referenced to the primary cesium fountain frequency standard CSF1 of PTB. The measurements were performed at an ambient temperature of 296 K, where the blackbody shift of the transition frequency is -0.37(5) Hz. The weighted average of the absolute frequency measurements is [3]

$$\nu(^{171}Yb^+) = 688\,358\,979\,309\,307.6\ (1.4)\ \text{Hz} \qquad (1)$$

This research is funded in part by grant RFP1-06-08 from the Foundational Questions Institute (fqxi.org) and by Deutsche Forschungsgemeinschaft in SFB 407.

Recent insights into the effects of collisions in fountain clocks [6] have led to a reduced uncertainty of the Cs fountain clock PTB-CSF1 and in turn allowed us to decrease the total relative uncertainty of the absolute frequency measurement of the $^{171}Yb^+$ standard to $2.0\cdot10^{-15}$. The main contribution to the systematic uncertainty of the $^{171}Yb^+$ standard of $1.5\cdot10^{-15}$ stems from the estimate on the quadrupole shift of the $^2D_{3/2}$ state due to the gradient of the electric stray field.

The instability of the 688 THz $^{171}Yb^+$ frequency standard reaches an Allan deviation $\sigma_y(\tau) = 2\cdot10^{-16}$ at $\tau = 3000$ s, consistent with the quantum projection noise limit for the experimental interrogation sequence. A further optimized sequence should allow to reach $\sigma_y(\tau) = 2\cdot10^{-15}\,(\tau/s)^{-1/2}$ [7]. The stability of the $^{171}Yb^+$ clock laser was measured by comparison with another similarly stable laser system, the probe laser of the Ca frequency standard at PTB [8]. The results indicate that the instability of the $^{171}Yb^+$ clock laser approaches the limit given by the thermal noise of the reference cavity. The model of Numata et al. [9] predicts a thermal 1/f noise floor corresponding to an Allan deviation of $\sigma_y = 8\cdot10^{-16}$ for our clock laser.

The level system of the $^{171}Yb^+$ ion also contains the long-living metastable $^2F_{7/2}$ state which decays to the ground state via an electric octupole transition and has a natural lifetime of approximately 6 yr. This transition at 642 THz has been investigated at NPL and proposed as an attractive candidate for an optical frequency standard with a virtually unlimited intrinsic line quality factor Q [10]. We have started to build up a new experimental setup which should enable us to observe this transition with sub-hertz resolution.

Using a femtosecond frequency comb generator, we intend to perform repeated measurements of the frequency ratio between the 688 THz and 642 THz $^{171}Yb^+$ frequency standards. In contrast to previous investigations [11, 12], the accuracy of such a local frequency comparison is independent of the limitations of microwave frequency standards and of long-distance time transfer techniques. The frequency ratio between the two investigated $^{171}Yb^+$ transitions is highly sensitive to changes of the fine structure constant α: if α changes, then the relative change of this frequency ratio is expected to be 6.2 times larger than that of α [13]. Thus the

1-4244-0647-1/07/$20.00 ©2007 IEEE

planned measurements constitute a particularly sensitive test of the constancy of the fine structure constant. The presently most stringent model-independent limit for $| d \ln \alpha / d t |$ can be deduced by combining data from $^{171}Yb^+$ at PTB and from $^{199}Hg^+$ at NIST [14], yielding a bound of $4 \cdot 10^{-16}$ yr^{-1}.

REFERENCES

[1] T. Schneider, E. Peik, Chr. Tamm, "Sub-Hertz optical frequency comparisons between two trapped $^{171}Yb^+$ ions," Phys. Rev. Lett., vol. 94, pp. 230801, 2005.

[2] S. G. Karshenboim: "Time and space variation of fundamental constants: Motivation and laboratory search," in Time and Matter, I. Bigi, H. Faessler, Eds. Singapore: World Scientific, pp. 26-42, 2006; arXiv:physics/0306180, 2003.

[3] E. Peik et al., "Laboratory limits on temporal variations of fundamental constants: An update," arXiv:physics/0611088, 2006.

[4] See, e.g., P. Gill et al., "Trapped ion optical frequency standards," Meas. Sci. Technol., vol. 14, pp. 1174-1186, 2003. *(and references therein)*

[5] F. Adler et al., "Phase-locked two-branch erbium-doped fiber laser system for long-term precision measurements of optical frequencies," Optics Express, vol. 12, pp. 5872-5880, 2004.

[6] K. Szymaniec et al., "Cancellation of the collisional frequency shift in caesium fountain clocks," Phys. Rev. Lett., vol. 98, pp. 153002, 2007.

[7] E. Peik, T Schneider, Chr. Tamm, "Laser frequency stabilization to a single ion ," J. Phys. B: At. Mol. Opt. Phys., vol. 39, pp. 145-158, 2006.

[8] T. Nazarova, F. Riehle, U. Sterr, "Vibration-insensitive reference cavity for an ultra-narrow-linewidth laser," Appl. Phys. B, vol. 83, pp. 531-536, 2006.

[9] K. Numata, A. Kemery, J. Camp, "Thermal-noise limit in the frequency stabilization of lasers with rigid cavities," Phys. Rev. Lett., vol. 93, pp. 250602, 2004.

[10] P. J. Blythe, S. A. Webster, K. Hosaka, P. Gill, "Systematic frequency shifts of the 467 nm electric octupole transition in $^{171}Yb^+$," J. Phys. B: At. Mol. Opt. Phys., vol. 36, pp. 981-989, 2003.

[11] M. Fischer et al., "New limits on the drift of fundamental constants from laboratory measurements," Phys. Rev. Lett., vol. 92, pp. 230802, 2004.

[12] E. Peik, B. Lipphard, H. Schnatz, T. Schneider, Chr. Tamm, "Limit on the present temporal variation of the fine structure constant," Phys. Rev. Lett., vol. 93, pp. 170801, 2004.

[13] V. A. Dzuba, V. V. Flambaum, M V. Marchenko, "Relativistic effects in Sr, Dy, Yb II, and Yb III and search for variation of the fine-structure constant," Phys. Rev. A, vol. 68, pp. 022506, 2003.

[14] T. Fortier et al., "Precision Atomic Spectroscopy for Improved Limits on Variation of the Fine Structure Constant and Local Position Invariance," Phys. Rev. Lett., vol. 98, pp. 070801, 2007.