Absolute frequency measurement of the In^+ $^1S_0$ - $^3P_0$ "clock" transition

J. von Zanthier, Th. Becker, M. Eichenseer, Ch. Schwedes, E. Peik, H. Walther
R. Holzwarth, J. Reichert, Th. Udem, T. W. Hänsch
A. Yu. Nevsky, P. V. Pokasov[1], M. N. Skvortsov[1], S. N. Bagayev[1]

Sektion Physik der Ludwig-Maximilians-Universität München and Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, 85748 Garching, Germany
Tel +49-89-32095-288, Fax +49-89-32095-200
E-mail: jvz@mpq.mpg.de, Website: http://www.mpq.mpg.de/Indium.html
[1] *Institute of Laser Physics, 630090 Novosibirsk, Russia*

Single laser-cooled ions stored in radiofrequency traps are the atomic systems which allow the highest resolution in optical or microwave spectroscopy. A narrow transition in such an ion can serve as a reference for a frequency standard of extremely high accuracy and stability. Such a frequency standard enables precise measurements of fundamental constants [1], the investigation of their possible variation in time [2] or stringent tests of QED or general relativity.

In view of this application we study the $5s^2\,^1S_0$ - $5s5p\,^3P_0$ transition in In^+ at a wavelength of 237 nm. This transition with a natural linewidth of only 0.82 Hz is highly immune to systematic frequency shifts [3]. A frequency control at the millihertz level is expected, leading to a residual uncertainty of 10^{-18} [4].

For such a frequency standard it is necessary to be able to compare its frequency to other frequencies, especially to the present primary frequency standard, the cesium atomic clock. As a first step to this end, we reported recently the measurement of the absolute frequency of the In^+ clock transition using as a reference a methane-stabilized He-Ne laser at 3.39 μm and a Nd:YAG laser at 1064 nm whose second harmonic was locked to a hyperfine component in molecular iodine [5]. The accuracy in this measurement of 3.3 parts in 10^{11} was limited by the uncertainty to which the iodine reference was known. Here we report on a new measurement of the absolute clock transition frequency linking the 237 nm radiation to the He-Ne laser alone. In this case the accuracy of the measurement is limited by the much smaller uncertainty of the He-Ne reference.

The frequency chain, used for the frequency comparison, consists of a diode laser at 848 nm phase-locked to the frequency-doubled light of a NaCl:OH^- color center laser at 1.70 μm which in turn is phase-locked to the second harmonic of the methane-stabilized He-Ne laser. The He-Ne standard has been calibrated before by a cesium atomic fountain clock to f_{He-Ne} = 88 376 182 599 976 (10) Hz [6]. A selected mode of the frequency comb of a mode-locked Ti:Sapphire femtosecond laser, frequency broadened by a standard single mode silica fiber, is phase coherently stabilized to the 848 nm laser. As the 76 MHz pulse repetition rate of the femtosecond laser is controlled by a local cesium atomic clock, each reference frequency of the comb is known with a fractional precision of a few parts in 10^{13} [6, 7]. A diode laser at 946 nm

is phase-locked to another selected mode of the comb, positioned 482 285 modes or 37 THz to lower frequencies from the initial mode at 848 nm. Its beat frequency with the 946 nm Nd:YAG laser whose 4th harmonic excites the In^+ clock transition is counted by a commercial radio frequency counter.

Excitations of the $^3P_0$ level are registered in optical-optical double-resonance while scanning the 946 nm Nd:YAG clock laser over the In^+ $^1S_0$ - $^3P_0$ transition [4]. Averaging the results of the eleven mesurement sessions we performed leads to a value for the absolute frequency f_{In^+} of the $^{115}In^+$ $^1S_0$ - $^3P_0$ clock transition of

$$f_{In^+} = 1\ 267\ 402\ 452\ 899.\ 92(0.23)\ \text{kHz}.$$

The uncertainty of 1.8 parts in 10^{13} is mainly due to the limited reproducibility of the He-Ne laser reference.

Systematic frequency shifts are small at the present level of accuracy. The main contribution is due to a Zeeman-shift estimated to be below 50 Hz. Other systematic frequency shifts due to e.g. quadratic Stark or second-order Doppler shifts are orders of magnitude smaller than the Zeeman-shift at the temperatures to which the ion is cooled in our trap (T $\sim$ 150 μK) [3].

For the future it is planned to use the frequency comb of the femtosecond laser to compare the Indium $^1S_0$ - $^3P_0$ transition directly to the cesium clock [8]. The stability and reproducibility of the $^1S_0$ - $^3P_0$ clock transition makes Indium an attractive candidate for such an ultra-precise frequency measurement.

A further interesting feature of the MPQ frequency chain is the fact that it can be used to compare two narrow optical transition frequencies with each other, e. g. the In^+ clock transition with the 1S - 2S transition in atomic hydrogen. This may allow the investigation of possible variations of fundamental constants in time [2].

The collaboration with the ILP, Novosibirsk, has been supported by the Volkswagen-Stiftung within Project No. I/72 607.

[1] Th. Udem, J. Reichert, R. Holzwarth, T.W. Hänsch, *Phys. Rev. Lett.* **82**, 3568 (1999)
[2] V.A. Dzuba, V.V. Flambaum, J.K. Webb, *Phys. Rev. Lett.* **82**, 888 (1999);
V.A. Dzuba, V.V. Flambaum, *Phys. Rev. A* **61**, 034502 (2000);
[3] Th. Becker et al., to be published;
E. Peik, G. Hollemann, H. Walther, *Phys. Rev. A* **49**, 402 (1994);
see also the corresponding poster at this conference
[4] H. Dehmelt, *IEEE Trans. Instrum. Meas.* **31**, 83 (1982)
[5] J. von Zanthier, J. Abel, Th. Becker, M. Fries, E. Peik, H. Walther, R. Holzwarth, J. Reichert, Th. Udem, T.W. Hänsch, A. Yu. Nevsky, M.N. Skvortsov, S.N. Bagayev, *Opt. Comm.* **166**, 57 (1999)
[6] P. Pokasov *et al.*, to be published.
[7] J. Reichert, R. Holzwarth, Th. Udem, T.W. Hänsch, *Opt. Comm.* **172**, 59 (1999)
[8] M. Niering, R. Holzwarth, J. Reichert, P. Pokasov, Th. Udem, M. Weitz, T. W. Haensch, P. Lemonde, G. Santarelli, M. Abgrall, P. Laurent, C. Salomon, A. Clairon, to be published;
see also the corresponding poster at this conference.