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Precision spectroscopy of cold strontium atoms, towards optical atomic clock

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Abstract. This report concerns the experiment of precision spectroscopy of cold strontium atoms in the Polish National Laboratory of Atomic, Molecular and Optical Physics in Toruń. The system is composed of a Zeeman slower and magneto-optical traps (at 461 nm and 689 nm), a frequency comb, and a narrow-band laser locked to an ultra-stable optical cavity. All parts of the experiment are prepared and the first measurements of the absolute frequency of the $^1S_0$–$^3P_1$, 689 nm optical transition in ^{88}Sr atoms are performed.

Key words: laser spectroscopy, cold atoms, optical atomic clock.

1. Introduction

Precision spectroscopy of atomic transitions has been at the basis of timekeeping (atomic clocks) for the past half-century. In particular, the SI unit of time, the second, is defined with respect to the frequency of resonance in ^{133}Cs atoms and atomic clocks are devices that realize such a definition. Techniques of laser cooling and trapping were used to significantly improve atomic clocks and resulted in construction of the fountain clocks. Even higher stability and accuracy is achieved in a new generation of atomic clocks, using optical transitions instead of the microwave ones (see review [1]). Optical clocks have already surpassed the stability of microwave clocks [2, 3] and reached inaccuracies below 10^{-15} with the expected control of systematic effects at the 10^{-18} level. Two types of optical clocks are possible: single ion clocks or neutral atoms in an optical lattice [4]. Clocks using the lattice show limited atom-atom interactions and offer the possibility of simultaneous measurements of large numbers of atoms; this increases the S/N ratio while tuning of the lattice laser to the magic wavelength eliminates the light-shift effects.

The $^1S_0$–$^3P_0$ transition in alkaline-earth atoms is a good candidate for the clock transition and, in particular, the clock using Sr atoms has been realized by the groups in Tokyo, Paris and Boulder [5–7]. Figure 1 shows the simplified level structure of Sr atoms with cooling and clock transitions indicated.

In this report we present the status of the experimental setup in the Polish National Laboratory of Atomic, Molecular and Optical Physics in Toruń aiming at the construction of Sr optical lattice clock. The first stage of the project has been completed which includes the optical frequency comb, the ultra-narrow band laser stabilized to an optical cavity of high finesse, and the apparatus for cooling and trapping of strontium atoms. All three elements are working well and first spectroscopic measurements have been performed.

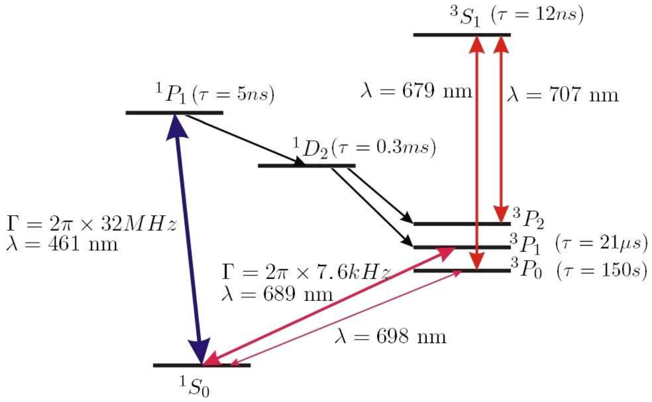

Fig. 1. Simplified level structure of Sr atoms with transitions used in the experiment: precooling – 461 nm, final cooling – 689 nm, clock transition – 698 nm, repumping – 679 and 707 nm

2. First stage atom cooling

The cooling process of strontium atoms is performed in two stages: the first is the precooling down to temperatures of a few mK, followed by ultimate laser cooling to temperatures below 10 μK. The first stage takes place in a blue magneto-optical trap (MOT). For this cooling the strong allowed transition $^1S_0$–$^1P_1$ is used at 461 nm. Strontium atoms have low vapour pressure so they are heated in an atomic oven to 500°C and form a beam within a vacuum set-up. To capture atoms in the MOT with reasonable loading rate, atoms in the beam have to be slowed in a Zeeman slower. The set-up is presented in Fig. 2. It is divided into two parts. The first one contains the

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atomic oven producing collimated strontium beam and laser beam collimation stage. The second part, with vacuum of the order of 10^{-10} mbar consists of a Zeeman slower and main chamber, where MOT is created. The Zeeman slower construction is described by Bober et al. [8]. It has the capture velocity of 450 m/s and produces atoms slowed down to 30 m/s. The flux at the oven temperature of 460°C is 3.5×10^9 s^{-1}. Blue MOT beams are detuned 40 MHz below the strontium $^1S_0$–$^1P_1$ transition and have 23 mm in diameter. To avoid the situation where cooling of the strontium atoms is interrupted by atoms relaxing not to the ground state, but to some other metastable states, two repumping lasers are used: 679 and 707 nm. In total 6–8×10^8 atoms are loaded into the blue MOT and cooled down to 2–3 mK. In the present construction the apparatus is optimized for cooling of bosonic ^{88}Sr but it can be rearranged for cooling of the fermionic ^{87}Sr.

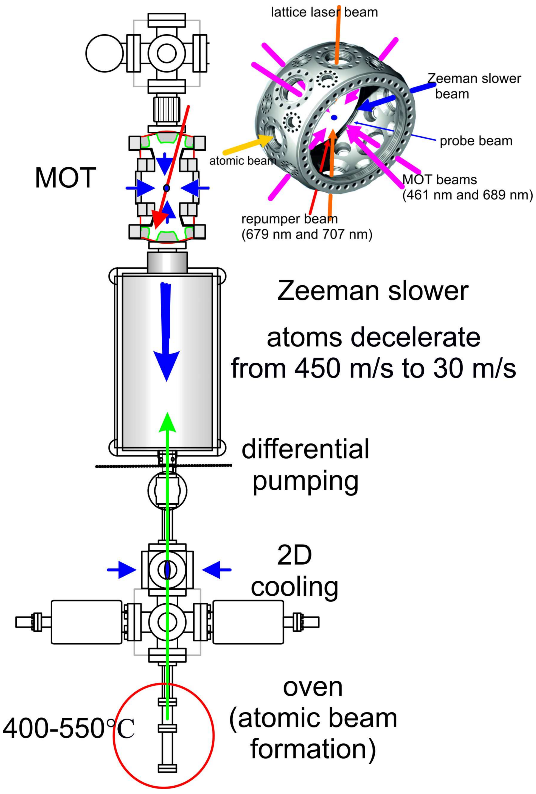

Fig. 2. Vacuum set-up. The inset shows the experimental chamber

3. Narrow band laser

A tunable diode laser system of ultra-narrow line width is used for ultimate precision spectroscopy on the doubly forbidden clock transition [9]. The laser is spectrally narrowed by locking it to a high-finesse optical cavity used as short-term frequency reference. The Pound-Drever-Hall locking configuration is used and an efficient laser line width narrowing is achieved. The cavity mirrors and the 100 mm spacer are made of ultra-low expansion glass. The mirrors are optically contacted to a spacer. The FSR of the cavity is 1.5 GHz and its finesse is F = 62800. The cavity should be insensitive to vibrations and to this end a special design of the cavity is used with the horizontal cylindrical shape with cutouts (see the photograph of the bare cavity in Fig. 3). The design is adopted from Webster et al. [10]. The proper choice of the support points assures immunity to vibrations. The cavity is isolated from the laboratory environment and enclosed in a vacuum chamber placed in another thermal enclosure. Vibration isolation platform (Minus-k, BM-1) and a steel chamber lined with acoustic-damping foam (Nova-scan NanoCube) assure good mechanical isolation. Two complete laser systems are constructed based on commercially available external cavity diode lasers (Toptica DLpro and DL100) which both provide about 20 mW output power at wavelength 687–693 nm. Each laser is independently locked to its own identical optical cavity with the use of the Pound-Drever-Hall locking method. To evaluate the laser linewidth a beat note between two independently locked lasers can be measured. A line width of about 8 Hz has been achieved in a preliminary measurement (see Fig. 4).

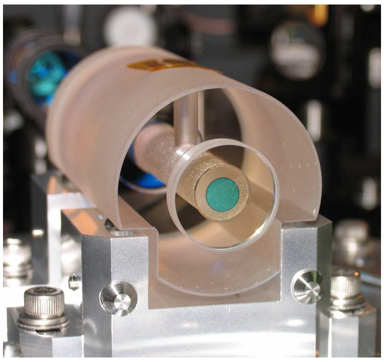

Fig. 3. High finesse optical cavity with the support structure

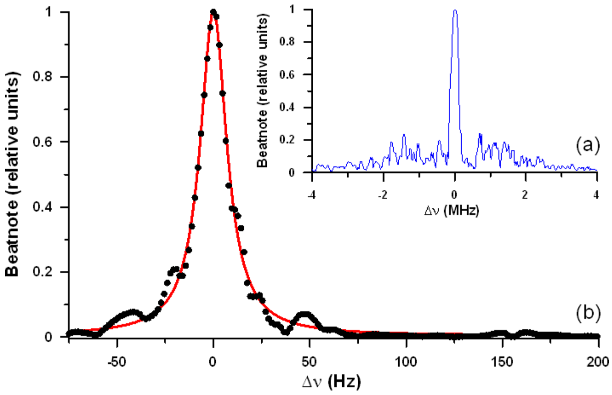

Fig. 4. Power spectrum of the beat note of two independently locked lasers: (a) resolution bandwidth 150 kHz, (b) resolution bandwidth 9 Hz. The width of the peak in (b) is 16.8 Hz

To achieve wide frequency tuning together with the narrow line width requirement, another configuration, called master-slave scheme, has been tested. In this setup one of the lasers is locked to the cavity and the other is phase-locked to the first one with the well-controlled offset up to several GHz. The relative phase lock of two lasers is better than 150 mHz. The main limitation in the current state of this setup is the temperature instability of the optical cavity. Its active stabilization to a few mK should result in the drift rate of the order of 1 Hz/s.

4. Spectroscopy and laser stabilization on the 689 nm transition

The simplified apparatus used for spectroscopy of the 689 nm transition is presented in Fig. 5. Laser beam from one of the ultra-narrow lasers has been coupled into a five-meter long, single mode, polarization maintaining fiber and sent to the strontium set-up. Cavity used for the ultra-narrow laser was not temperature stabilized and laser frequency was slowly drifting. A second Toptica DLpro laser was locked to the master laser using the offset lock technique and was used for spectroscopy. The frequency tuning required for the spectroscopy measurements was assured by passing the laser beam twice through an acousto-optical modulator (AOM). The beam, expanded to 5 mm diameter, was crossing the atomic beam perpendicularly and was precisely retro-reflected. In order to avoid any influence of stray magnetic fields on the spectroscopy measurement, the $^{1}S_{0}(m=0)$–$^{3}P_{1}(m=0)$ transition was chosen which is insensitive to the Zeeman shift. Additionally, magnetic field of 1 mT directed parallel to the atomic beam was imposed and laser beam had pure π polarization. Fluorescence signal was detected with a photomultiplier. Exemplary signal, showing narrow sub-Doppler structure of the $^{1}S_{0}(m=0)$–$^{3}P_{1}(m=0)$ transition in ^{88}Sr (689 nm line) is presented in Fig. 6.

Using a frequency comb produced by a fiber laser an absolute transition frequency was measured with respect to a commercial Rb 10 MHz reference. This measurement, done as a test, was limited by the reference accuracy. In the next step, the cavity-drift cancellation system has been build and used for locking the laser to the atomic transition frequency. Figure 5 shows the red laser set-up with the offset lock, and the scheme of its locking to the atomic transition. In the locking scheme AOM2 modulated the frequency of the beam which was used for spectroscopy. Levels of the fluorescence signals from both sides of the atomic resonance were compared and correction for cancellation of the drift was calculated for AOM1 in the ultra-narrow laser path. This locking set-up can also be applied in the future for locking of the 698 nm laser to the strontium clock transition.

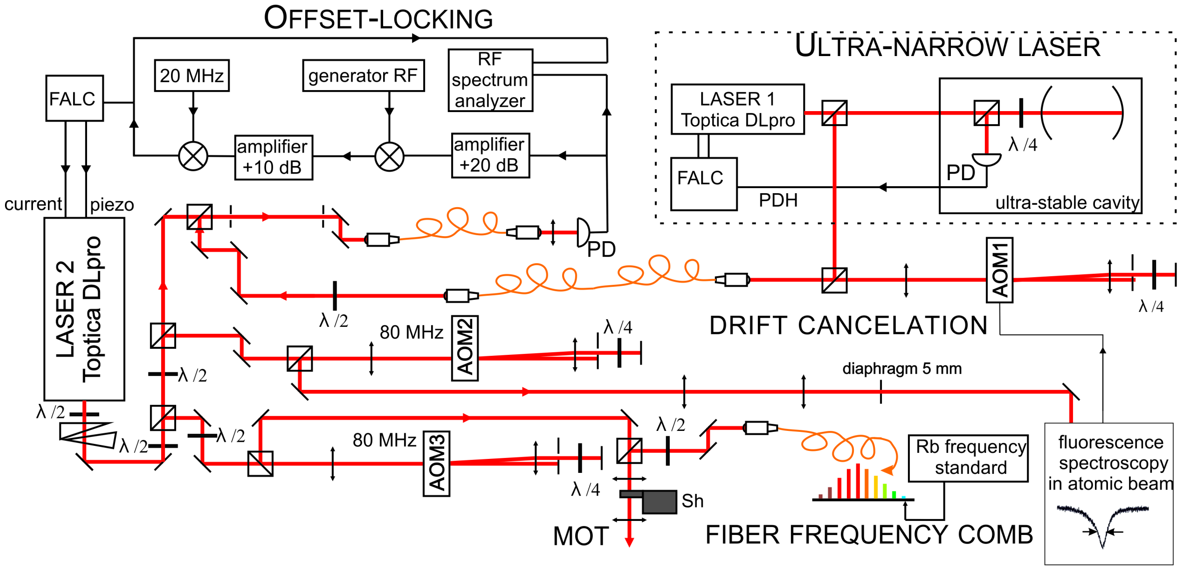

Fig. 5. Scheme of the spectroscopy of 689 nm transition. The whole red laser set-up with offset lock, and locking to atomic transition scheme is presented. The absolute laser frequency is referenced to the optical frequency comb

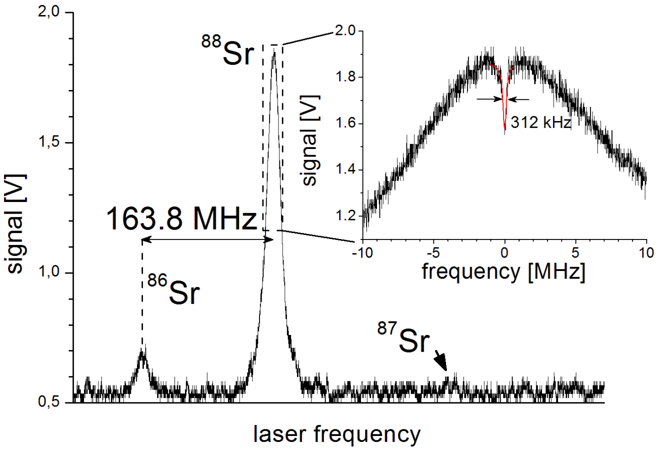

Fig. 6. Spectroscopy of the of ^{88}Sr $^{1}S_{0}(m=0)$–$^{3}P_{1}(m=0)$ line (689 nm). The lower trace shows the wide scan, the inset shows detail of the Doppler-free feature in the center

5. Second stage cooling and trapping

With the 689 nm laser stabilized to the strontium transition we created the red MOT. The red MOT beams had 8 mm diameter and were superimposed on the blue MOT beams. The magnetic field gradient was lowered from about 0.68 T/m during the blue MOT phase to 0.03 T/m at the beginning of the red MOT phase and then the cloud was compressed by linearly ramping the field to 0.10 T/m. The natural width of the $^1S_0$–$^3P_1$ transition at 689 nm is much less than the Doppler width of this transition even at a temperature of a few mK – temperature of atoms in the blue MOT. In order to transfer as many atoms as possible from the blue trap, the narrow band red laser beams had to be artificially broadened. They were modulated with 16 kHz frequency and modulation depth of 1 MHz. As a result, up to 10^7 atoms of ^{88}Sr were stored and cooled to temperature below 15 μK. To detect the atoms in the red MOT the laser beam at 461 nm, resonant with the strong $^1S_0$–$^1P_1$ transition was used. In this way the difficulties in detection of faint red fluorescence were avoided.

6. Conclusions and outlook

In the first stage of the project the main elements of the apparatus for the optical atomic clock with Sr atoms have been built: the optical frequency comb, the ultra-narrow band laser stabilized to an optical cavity of high finesse, and the apparatus for cooling and trapping of strontium atoms. First spectroscopic measurements have been performed as a test of the system integration. The system is designed for the bosonic ^{88}Sr atoms, but operation with the fermionic ^{87}Sr atoms can be achieved after minor modifications. In a second stage of the project the clock transition $^1S_0$–$^1P_0$ (698 nm) is investigated. To this end the atoms are to be captured in the magic wavelength optical lattice. The ultra-narrow band laser is tuned to the 698 nm transition and its bandwidth further is decreased. The active stabilization of the optical cavity is implemented assuring low drift of the laser.

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