Optical frequency standard with ultra-cold strontium atoms

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We report on our progress toward the realization of an optical frequency standard referenced to strontium intercombination lines. While first frequency measurement of the weakly allowed $^1S_0$-$^3P_1$ transition was done with saturation spectroscopy on a thermal beam, we are preparing the experimental setup for high resolution spectroscopy on ultracold atoms of the doubly forbidden $^1S_0$-$^3P_0$ line. Our current setup allows the capture more than 10^7 atoms at 1 μK in 500 ms in two stages of magneto-optical trapping. We also demonstrated the dipole trapping of ultracold strontium isotopes for accurate spectroscopy and collisional measurements. A semiconductor laser source at 698 nm has already been locked to a pre-stabilization cavity obtaining a fast linewidth of less than 1 kHz. Second stage stabilization of the clock laser to ultra-high finesse cavity is in development. Recent measurement of elastic and inelastic cross-sections of the two most abundant ^{88}Sr and ^{86}Sr isotopes are also presented.

I. INTRODUCTION

Thanks to the ultra-narrow intercombination transitions, strontium has recently become the object of intense study in the field of optical frequency metrology [1]. These studies open the way to the realization of a new optical frequency standard with unprecedented stability and accuracy. Proposals based on different interrogation schemes for both fermionic (^{87}Sr) and bosonic (^{88}Sr, ^{86}Sr, ^{84}Sr) isotopes have been put forward (optical lattice clock [2], engineered atom clock [3, 4, 5, 6]) suggesting the possibility to reach the 10^{-17} level of overall accuracy. Indeed, thanks to the higher oscillator frequency, a clock in the optical domain could potentially reach a stability level of 10^{-18} at 1 s [2] which represents a factor of 10^4 improvement with respect to the best microwave standards [7]. A clock with such stability and accuracy could be used as a powerful test for relativistic theory, searching for deviations of fine structure constant and to define a new atomic time standard. The high stability optical clock signals would find direct application in deep space navigation, remote sensing, secure telecommunications and ultra-precise geodesy.

The level scheme allows the possibility to efficiently cool strontium with standard Doppler cooling techniques to temperature well below 1 μK in hundreds of milliseconds using two steps of trapping and cooling in magneto-optical trap, working first on the dipole allowed $^1S_0$-$^1P_1$ at 461 nm and, subsequently, on the $^1S_0$-$^3P_1$ transition at 689 nm. The fast cooling process toward μK temperatures enables short cycle times, relaxing the demands on frequency stability of the clock laser source used for interrogating the transition [8].

The possibility to cool strontium atoms with visible light, easy reachable with semiconductor source, is in turn interesting from the point of view of realizing compact and portable source of cold atoms to be used in future application both on earth and in space.

Moreover, bosonic ^{88}Sr isotopes have already been trapped in pure optical dipole traps at high phase-space densities of $\rho = 0.1$ [9, 10]. While further increase of ρ with standard evaporative cooling technique is limited by the very low elastic cross section at low temperatures of ^{88}Sr atoms, different cooling techniques, based on sympathetic cooling with isotopic mixtures can be applied [10].

Finally, due to both the special strontium level structure and its cold collision properties, ultra-cold ^{88}Sr has been demonstrated to be particularly suited for applications in the field of quantum sensor. Long lived Bloch oscillation of ^{88}Sr atoms in a vertical standing wave trap has been reported, enabling high sensitive measurement of gravity forces [11].

The structure of the article is the following. Section 2 describes the previous absolute frequency measurements of intercombination lines $^1S_0$-$^3P_1$ of strontium. In section 3, 4 and 5 we present the work in progress for preforming spectroscopy on the doubly forbidden $^1S_0$-$^3P_0$ transition for bosonic isotopes. Section 6 describes the apparatus for cooling and trapping strontium atoms, while section 7 and 8 describes the latest results obtained with cold atoms trapped in optical dipole traps, mainly concerning cold collision physics and Bloch oscillations of ^{88}Sr atoms in 1D vertical standing wave trap.

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II. FREQUENCY MEASUREMENT OF THE $^1S_0$-$^3P_1$ TRANSITION

Our first setup was used for the absolute frequency measurement of the $^1S_0$-$^3P_1$ intercombination line of ^{88}Sr and ^{86}Sr isotopes at 689 nm ($\Gamma/2\pi$ = 7.6 kHz). For the absolute frequency measurement we used a fs-optical-comb-generator; details of the experimental apparatus can also be found in [12]. Part of the light coming from a pre-stabilized 689 nm source (extended cavity diode laser - ECDL - tightly locked to Fabry-Perot cavity with finesse of about 10^4) is coupled into a polarization maintaining fiber and delivered to a strontium thermal atomic beam, while a second light beam is sent towards the comb with a 20 meter long fiber. From the frequency noise measured with a second independent cavity we can infer a linewidth of 20 Hz for the 689 nm source [13].

With standard saturation spectroscopy techniques we obtained a sub-Doppler signal used for long term stabilization of the length of the cavity. The values measured for the two most abundant isotopes are 434 829 121 311 (10) kHz for ^{88}Sr and 434 828 957 494 (10) kHz for ^{86}Sr. The latter value has been derived by difference from the measurement of the ^{88}Sr-^{86}Sr isotopic shift (163 817.4 (0.2) kHz). In the absolute frequency measurement, one of the main limitation was found to be the instability of our GPS referenced quartz oscillator used as frequency reference for the comb [12, 14]. These values are consistent with other determinations with spectroscopy on cold atoms both at SYRTE [15] and at JILA-NIST laboratories [16].

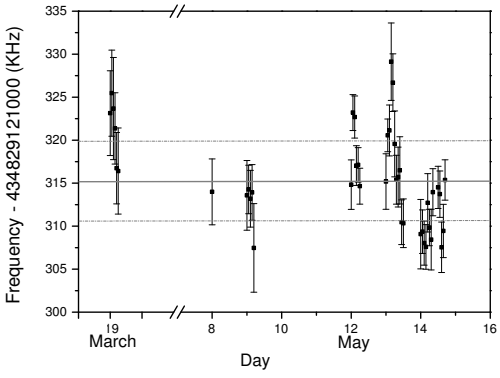

FIG. 1: Frequency measurement of the intercombination line $^1S_0$-$^3P_1$ for the bosonic ^{88}Sr atoms. The data points are the mean values of a set of measurement over 200-300 s, while the error bars are the standard deviation over each set. The final corrected value for ^{88}Sr is 434 829 121 311 (10) kHz

While the ultimate performance of an optical clock working on the $^1S_0$-$^3P_1$ transition for the most abundant ^{88}Sr isotope is limited by the linewidth of the transition (stability 10^{-14} at 1 s, accuracy 10^{-15}[17]), a clock working on the doubly forbidden $^1S_0$-$^3P_0$ transition could overcome the limitations both in stability and accuracy.

III. SPECTROSCOPY ON THE DOUBLY FORBIDDEN $^1S_0$-$^3P_0$ TRANSITION FOR ^{88}SR

The most interesting transition in strontium for the realization of an optical frequency standard is the doubly forbidden line $^1S_0$-$^3P_0$ at 698 nm. Within the framework of the optical lattice clock [2], spectroscopy on this line could produce a frequency reference in the optical regime with unprecedented level of accuracy and stability. In the fermionic (^{87}Sr) isotope the hyperfine mixing due to a non-zero nuclear spin ($I = 9/2$) gives a finite lifetime for the $^3P_0$ state allowing the possibility to observe the transition with direct spectroscopy schemes. Spectroscopy of ^{87}Sr trapped in 1D optical lattices at the magic wavelength, has already been performed in other labs [2, 18, 19].

The case of the bosonic isotopes is different: the nuclear spin is zero and the transition is forbidden at all the orders; in this case different techniques have to be used. Recently many spectroscopic schemes have been proposed to "engineer" the clock transition by mixing the metastable $^3P_0$ level with other short living upper levels, by the use of other coupling light field [3, 4], by trapping the atoms in optical lattice done with elliptical polarization [6], or by using a static magnetic field [5]. While the former schemes are experimentally more complex, the most promising seems to be the one that uses a static magnetic field to mix the $^3P_0$ and $^3P_1$ levels.

Following the treatment in ref. [5] it is possible to calculate the induced transition rate V_{12} for the $^1S_0$-$^3P_0$ transition with a fixed applied $\mathbf{B}$ field and a fixed light intensity I resonant with the $^1S_0$-$^3P_0$ transition. The transition rate is given by the equation $V_{12} = \alpha\sqrt{I}|\mathbf{B}|$, (where $\alpha^{\mathrm{Sr}} = 99\,\mathrm{Hz/T}\sqrt{\mathrm{mW/cm^2}}$ [5]) while the fraction of the state $^3P_1$ mixed to the $^3P_0$ is given by the ratio of the Rabi frequency $\omega_{\mathbf{B}}$ and the fine structure energy splitting Δ_{32} between the two states $^3P_0$ and $^3P_1$ ($\Delta_{32}{}^{\mathrm{Sr}}/2\pi$=5.6 THz).

Within this framework it is possible to calculate the quadratic Zeeman correction for the $^1S_0$-$^3P_0$ transition $\Delta_{\mathbf{B}} = \beta|\mathbf{B}|^2$, and the AC Stark shift is $\Delta_L = kI$ where the two coupling constant for strontium have been calculated to be β^{Sr}=-23.3 MHz/T^2, k^{Sr} =-18 mHz/(mW/cm^2) [5].

If one considers a magnetic field of $|\mathbf{B}| = 10$ gauss ($\pm$ 1 mgauss) and an intensity of the interrogating light of $I = 10\,\mathrm{mW/cm^2}(\pm 1\%)$, the fraction of the state $^3P_1$ mixed is $\omega_{\mathbf{B}}/\Delta_{32} = 2 \times 10^{-6}$, giving a transition Rabi frequency of $V_{12} \sim 0.3$ Hz.

Due to this very small contribution of state $^3P_1$ to the mixture, the sensitivity to lattice light polarization

is reduced to about 500 mHz/rad. The correction for quadratic Zeeman effect for the $^1S_0$-$^3P_0$ transition is $\Delta_{\mathbf{B}} = -23.3\,\mathrm{Hz}(\pm 5\,\mathrm{mHz})$, and the AC Stark shift is $\Delta_L = -180(2)\,\mathrm{mHz}$.

It seems reasonable that using this scheme, spectroscopy on the $^1S_0$-$^3P_1$ transition could be performed with an overall accuracy of some parts in 10^{-17}.

The $^1S_0$-$^3P_0$ transition in ^{88}Sr has not been observed yet, but its frequency can be calculated from the value reported in [15] with an accuracy of about 100 kHz. In order to find the first time the transition it is possible to increase the transition probability by increasing both the intensity of the interrogating light and the intensity of the static magnetic field. In our experimental system, the maximum intensity of the interrogating light is about $I_{\max} \sim 1\,\mathrm{W/cm^2}$ where the maximum magnetic field at the center of the trap is of the order of $\mathbf{B}_{\max} \sim 100\,\mathrm{gauss}$. The maximum transition frequency rate is then $V_{12}{}^{\max} = 30\,\mathrm{Hz}$.

While this transition has never been observed for bosonic isotope of strontium, this spectroscopy scheme has already been applied to observe the $^1S_0$-$^3P_0$ transition in bosonic ^{174}Yb atoms [20].

The experimental setup for magnetic-field induced spectroscopy is reported in details in ref. [20]. The spectroscopy is done with atoms trapped in 1D optical lattice at magic wavelength. The red interrogating light is superimposed to the trapping light with a dichroic mirror and focused with an achromatic lens.

IV. ULTRA-STABLE LASER SOURCE AT 698 NM

For performing spectroscopy on the doubly forbidden $^1S_0$-$^3P_0$ line of strontium we are preparing a 698 nm ultra-stable source based on a semiconductor ECDL stabilized in two steps with two cavities of increasing finesse [21]. The source is pre-stabilized with standard Pound-Drever-Hall lock scheme to the same medium finesse cavity used for the stabilization of the 689 nm laser resonant with the $^1S_0$-$^3P_1$ transition. In order to reduce the RF pick-up between the two servo electronics, we used different RF frequency to drive the two electro-optic modulators working at the two different wavelength. With this stage of stabilization the fast linewidth of the laser has been reduced to about 700 Hz. While there is room to reduce the high frequency noise of the laser by optimizing the servo electronics, already long term stability at sub-kHz level is achieved by locking to this resonant cavity, whose length is stabilized to the $^1S_0$-$^3P_1$ transition [12]. Part of the light is then delivered to the high finesse cavity for second stage stabilization. The new high finesse cavity is realized with a specially cut 10 cm ULE spacer for symmetric horizontal suspension [22, 23, 24]. The ULE spacer (Corning 7972) has a turning point for temperature expansion coefficient near room temperature (20°C-25°C), with a residual sensitivity of less than $10^{-9}/°\mathrm{C}$. Two SiO_2 mirrors are optically contacted to both ends of the spacer. The mirrors have a transmission coefficient of 3 ppm (loss due to scattering and absorption < 1 ppm), giving a finesse of about 5×10^5, while the use of silica mirrors, could reduce the mechanical fluctuation induced by thermal noise as pointed out in recent works [25, 26].

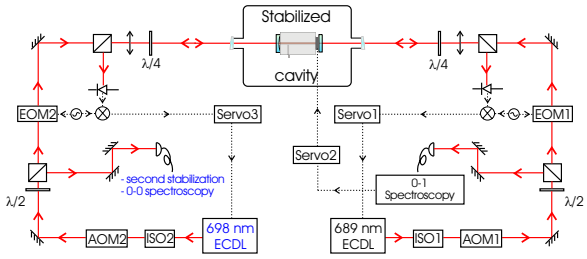

FIG. 2: *Experimental setup for clock laser at 698 nm. The ECDL laser is pre-stabilized on the same cavity used for the stabilization of the light at 689 nm, resonant with the $^1S_0$-$^3P_1$ transition of strontium. Second step of stabilization is done with a frequency lock to a fringe of high-finesse cavity. ECDL extended cavity diode laser, AOM acusto-optical modulator, EOM electro-optical modulator, ISO optical isolator.*

With a temperature stabilization of the cavity of the order of 10 mK and seismic noise acceleration of the order of $1\,\mu g_{rms}$, we expect a sub-Hz long term stability of the cavity length.

V. TRAPPING LASER AT 813 NM

The laser source we are preparing for optical dipole trapping at magic wavelength is a single mode tunable infrared source at 813 nm based on a master ECDL plus a tapered amplifier laser. The maximum optical power is 650 mW. The 1D standing wave trap is then obtained by focusing the light to the atom region and retro-reflecting back the light. With a waist of 30 μm we calculate a maximum trap depth of U_0=30 μK, with a scattering rate $\Gamma_s = 0.6\,\mathrm{s}^{-1}$.

With similar trap geometry done at slightly different wavelength we have observed an atom transfer efficiency from the MOT of the order of 10% [27]. It is then possible with our experimental setup to trap more than 10^6 ^{88}Sr atoms in less than 1 s with lifetimes of the order of 5 s.

VI. TRAPPING AND COOLING STRONTIUM

Strontium atoms are first trapped from a slowed and collimated atomic beam in a magneto optical trap operated on the dipole allowed $^1S_0$-$^1P_1$ transition at 461 nm. Further details on the experimental setup can be found in [27].

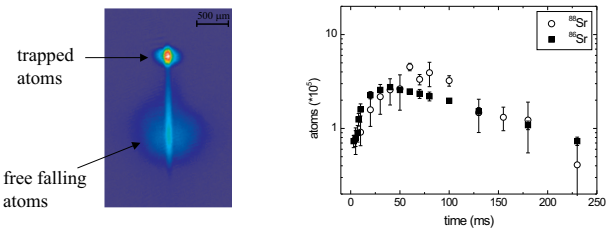

FIG. 3: Crossed-beams FORT loading. The inset shows an in-situ image of trapped atoms. The graph shows the measured FORT population as a function of the time overlap between FORT and red MOT.

The beam is originated by evaporating strontium in an oven at typical temperature of 500°C. The loading in the blue MOT is further improved with the use of a green repumping laser at 497 nm resonant with the $^3P_2$-$^3D_2$ transition. Typically we trap more than 2×10^8 ^{88}Sr atoms in 200 ms at a temperature of 2 mK. The cooling then proceeds with a second stage Doppler cooling working on the intercombination $^1S_0$-$^3P_1$ line. For this, the red light produced with slave laser optically injected with light coming from frequency stabilized master source at 689 nm, is superimposed with the blue light used for the first trapping. Typically more than 10^7 ^{88}Sr atoms at 1 μK are prepared for subsequent transfer into pure optical dipole trap.

With a small change in our setup we prepare an isotopic mixture of bosonic ^{88}Sr and ^{86}Sr isotopes. We start accumulating ^{88}Sr and ^{86}Sr in the $^3P_2$ magnetic trappable state [28], then, the blue laser is turned off and the repumper is flashed on for a few ms. This puts the atoms back in their singlet ground state where we proceed with the second-stage cooling, recapturing them into a red double MOT operated with two slave lasers tuned to the different isotopes. During the last 50 ms of MOT operation the dipole trap laser is superimposed to the MOT allowing the transfer of the mixture in the dipole trap. The number of atoms finally trapped in the dipole trap depends mainly on the time sequence in the first collection in the magnetic trap. At maximum we have obtained more than 10^6 ^{88}Sr atoms and 3×10^5 ^{86}Sr atoms.

VII. COLLISIONAL MEASUREMENT ON ^{88}SR^{86}SR

Optical dipole traps are the best environment for the study of collisional dynamics of ultracold atoms. This study, being of fundamental importance for understanding the possibility to reach quantum degeneracy with standard evaporative technique, is also crucial for understanding the dynamics at low temperatures for ultra-sensitive spectroscopy.

TABLE I: Sr collisional cross-section

elastic cross-section	
σ_{88-88}	$3(1) \times 10^{-13}$ cm^2
σ_{86-86}	$1.3(0.5) \times 10^{-10}$ cm^2
σ_{88-86}	$4(1) \times 10^{-12}$ cm^2
inelastic parameter	
K_{88}	$< 10^{-27}$ cm^{6}s^{-1}
K_{86}	$1.0(0.5) \times 10^{-24}$ cm^{6}s^{-1}

More specifically, we evaluated the elastic cross-sections σ_{i-j} $(i, j = 86, 88)$ for both intra and inter-species collisions, and the three-body recombination coefficients K_i $(i = 86, 88)$ in the FORT. The elastic cross-sections were deduced by driving the system out of thermal equilibrium and measuring the thermalization rate together with the sample density. For the inelastic collisions, we measured instead the density dependence of the trap loss rate. The results [10] are summarized in table I.

Our results show significant differences in the collisional properties of the two isotopes. Both the elastic cross-section and the three-body collision coefficient were found to be several orders of magnitude larger in ^{86}Sr than in ^{88}Sr and consistent with recent independent measurements of the scattering length [29, 30], while the inter-species cross-section σ_{86-88} is much larger than the intra-species cross-section σ_{88-88}. The results obtained indicate that forced evaporation toward BEC would be difficult for both ^{88}Sr and ^{86}Sr isotopes. The large interspecies elastic cross section instead could be used in order to perform an optical sympathetic cooling scheme of a large cloud of an isotope with a small cloud of the other isotope. With this technique a reduction of a factor of two of the temperature of a cloud of ^{88}Sr atoms has been obtained applying optical cooling to the other species (^{86}Sr) [10].

VIII. CONCLUSION

We presented our progress toward the realization of an optical frequency standard based on strontium intercombination transition. High resolution spectroscopy on the doubly-forbidden $^1S_0$-$^3P_0$ transition can be performed also in the more abundant even isotope at the level of 10^{-17}, and we are preparing the experimental setup consisting of clock laser and trapping laser at magic wavelength.

Interesting collision properties of bosonic strontium atoms at low temperatures have been exploited allowing the possibility to apply different cooling techniques. More recently, trapped ^{88}Sr atoms in a vertical 1D lattices has been demonstrated to be a highly sensitive sensor of gravity forces, well suited for application in measurements at short distances.

Funding has provided by ASI, INFM, INFN, and

Cassa di Risparmio di Firenze.

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