Investigation of the improvement method of number of atoms in the magneto-optical trap

Mikhail Guennadievitch Gurov and Elena Guennadievna Gurova

Novosibirsk State Technical University, Av. K. Marx 20, Novosibirsk, 630073, Russia

Abstract. In this paper the method of singlet repumping of strontium atoms was investigated. The calculations of the levels populations for this case were presented. With help of these calculations the dynamic of the magneto-optical trap was investigated also. The detailed description of the experiment was presented. During of this research the improvement of the number of atoms in magneto-optical trap by factor of 2 was obtained.

[Gurov M.G., Gurova E.G. **Investigation of the improvement method of number of atoms in the magneto-optical trap.** *Life Sci J* 2014;11(12s):620-623] (ISSN:1097-8135). http://www.lifesciencesite.com. 133

Keywords: repumper, blue line laser, strontium, magneto-optical trap

Introduction

Magneto-optical traps (MOT) are main part of the optical clocks and experiments with cold atoms [1-3]. Increasing of the number of atoms in MOT is one of the tasks of the quality experiment. During formation of the MOT atoms, for example, strontium in non-fully closed transition, can fall in dark states and drop out from cooling process lead to losses of signal atoms. But if we will shine atomic cloud by addition radiation, we can prevent atomic leakage to non-cooling states. This process has name "repumping process". Early only triplet repumpers were investigated for strontium MOT [3, 4].

In this paper the singlet channel was investigated as alternative for MOT improvement. The calculations of the populations and verifying experiment will be described in this research of ^{87}Sr MOT.

Diagram of the strontium levels

Due to MOT formation part of the ^{87}Sr atoms transfer to long-life dark state $(5s5p)^3P_2$ through intermediate state $(5s4d)^1D_2$. In this research the repumping from state $(5s4d)^1D_2$ to state $(5s12p)^1P_1$ is investigating. $(5s^2)^1S_0$ и $(5s5p)^1P_1$ is cooling transition with wavelength 461 nm. On Fig.1 singlet part of the strontium levels is shown [3-11].

The arrows show stimulated and spontaneous transitions. Main cooling transition between levels $(5s^2)^1S_0$ and $(5s5p)^1P_1$ (460 nm) is shown by thick blue line. Symbols (N_1, N_2,... and etc.) near the levels are labels of the levels introducing for simplicity of calculations. Numeric values after wavelength are Einstein's coefficients.

Transition $(5s5p)^1P_1$ - $(5s4d)^1D_2$ leads to atomic escape from cooling process and further these atoms fall in relatively long-life triplet levels. There is possibility to intercept atoms in state $^1D_2$, and transfer them on another, more convenient, levels, for example, with using of $(5s4d)^1D_2$-$(5s12p)^1P_1$ with wavelength 407.72 nm. In this research main attention was concentrated on investigation of transition $(5s4d)^1D_2$ - $(5s12p)^1P_1$ (blue line of the optical spectrum). Losses of the strontium MOT are coupled with collisions. Collisions lead to changing of energy states of the atoms. In details this type of the losses was described in [12]. Distribution of the rates filling and emptying of the MOT in system can be described by rate equations [13].

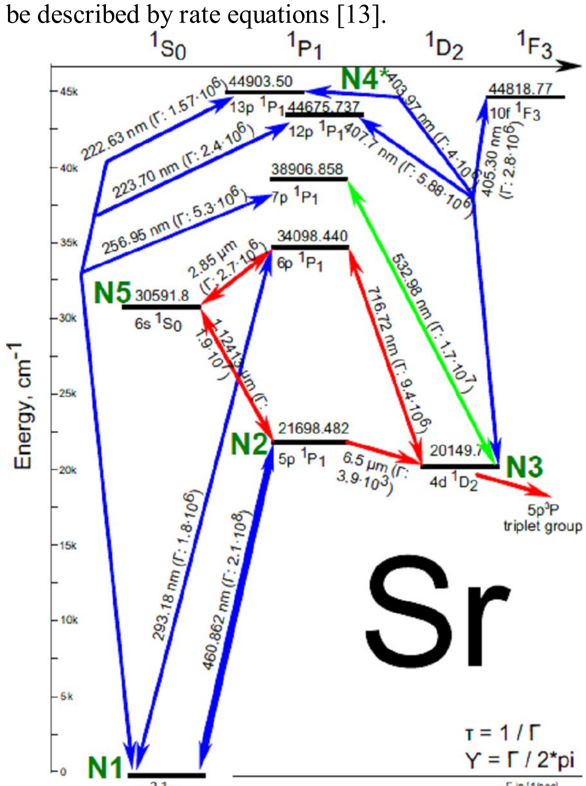

Fig.1. Wavelength and decay rates of the ^{87}Sr working transitions

The dynamic processes in the MOT

The main principle of repumping is redirection of all possible leakages from cooling processes. Cycle of the cooling process is loading atoms to the MOT. The main cooling transition

$(5s^2)^1S_0$ - $(5s5p)^1P_1$ and singlet transitions are shown on Fig.1. Set of the equations in Appendix A takes to account the levels N_1, N_2, N_3, N_4, and have not labeled, but involved in calculations levels of the triplet group. The lifetimes, rate of the MOT loading, losses and etc. are taken to account also. Due to this reason the method of the rate equations was used. Efficient rate of the MOT loading R was estimated as 10^8 (at/s). Parameter of the stimulated rate L_{ij}([Delta],I_{ij}), which was introduced in [14]:

$$L_{ij} = \frac{\left(\frac{\Gamma_{ij}}{2}\right)^2 \cdot \left(\frac{I_{ij}}{I_{sat_{ij}}}\right)}{\Delta_{ij}^2 + \left(\frac{\Gamma_{ij}}{2}\right)^2}, \qquad (1)$$

where [Delta]$_{ij}$ – detuning of the laser from transition frequency.

After introducing of the losses coefficient and introducing of the additional repumper influence we obtained the new set of the equations (Appendix B). In that case we need to note that losses of another level are not taking to account.

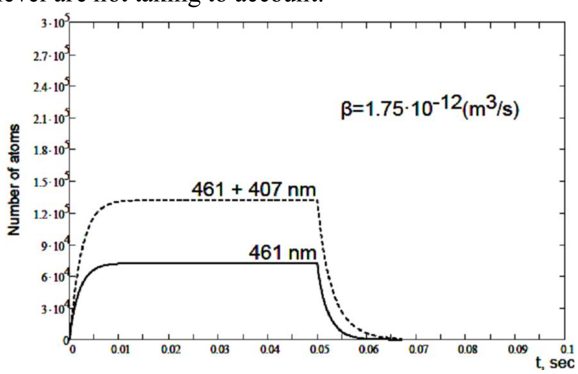

Fig.2. Calculated characteristics of the number of ^{87}Sr atoms on the level N_2 with radii of the MOT = 1 mm for losses [beta]=$1.75 \cdot 10^{-12}$(m^3/sec). Number of MOT atoms with presence of the 461 nm ($5s^{2\,1}S_0$-$5s5p\,^1P_1$) and 407 nm ($5s4d\,^1D_2$-$5s12p\,^1P_1$) (black dashed line) radiations with addition repumper (black solid line), is shown as function of time. Improvement of the number of atoms with addition repumper laser is estimated by factor of ≈1.8-2.0

For regular MOT the losses [beta] were $\approx 10^{-12}$ m^3/sec at diameter of the MOT ≈1 mm. To compare our results with and without rempumper laser, we need to compare calculation results from set of the equations from Appendix A and Appendix B. The results of the calculations of the populations dynamic are shown on Fig.2. Relatively small influence of the repumping laser is coupled with unaccounted, fast enough, decay channel from N_4 on N_1.

Experiment

Experimental installation, which was used for research, is shown on Fig.3. Experiment was made with installation of ^{87}Sr optical clocks with MOT 1 and optical lattice 813 nm. Observation of the atomic cloud was performed with EM-CCD camera Hamamatsu (Fig.3,a) C9100-02, which has max gain 2000 times and ability of record in real-time mode with frame rate >30 Hz, full resolution and clock frequency of 35 MHz under guiding of state-of-the-art software. Control of the wavelength and frequency was performed by wavemeter "Angstrom WS-U High Finesse" with absolute accuracy 2 MHz and accuracy of linewidth determining 100 MHz. For stabilization of the wavelength the side-order of the grating in Litrow scheme was used (Fig.3,a).

To transfer the atoms to the level $(5s12p)^1P_1$, the special laser with optical intensity higher than required for saturation has been made. For transition $(5s4d)^1D_2$ - $(5s12p)^1P_1$ the optical power was 5 mW, and size of the beam $1/e^2$ was 1 mm, intensity of the laser radiation was I_0=636 mW/cm^2, this was value sufficiently higher than appropriate saturation intensity I_{sat}=1.8 mW/cm^2.

Repumping laser was designed as Litrow scheme with holographic grating, which has been mounted on piezo with working displacement 1 [mu]м. Laser box (Fig.3,a) had double thermostabilization: PID- and relay stabilization for laser mount and cavity plate respectively. Diode was tuned on required wavelength 407.72 nm under the current 70 mA. The schematic of the experiment and view of the laser are shown on Fig.3a and b, respectively. Frequency of the laser fluctuated in time near the required central line and because of this fact the specific modulation of the injection current and voltage of the piezo has been added. The line of the laser Sanyo “DL-5146-101S” became wider and covered this fluctuations.

When check of the improvement nature of number of MOT atoms has been shown that the influence on atomic cloud was and under detuning of the repumper laser from resonant wavelength and with shutting of the laser beam of the repumper laser. The typical view of the plot, which was obtained during of this check is shown on Fig.4. In our research the agreement of the experimental and calculation data was obtained. Numeric estimation of the repumper laser influence is 1.9-2.0.

Conclusion

Singlet repumping channel in MOT of the group ($^1P_1$) with possibility of increasing of the atoms was investigated theoretically and experimentally. The calculations of the populations for ^{87}Sr atomic cloud with taking to account the losses for exited level $(5s5p)^1P_1$ has been suggested. The some estimation of the number of atoms dynamic was obtained also. The set of the equation, which describes evolution in time of the population of the energy levels with repumper laser was presented. Due to experiment the improvement of number of atoms was estimated by factor of 2.

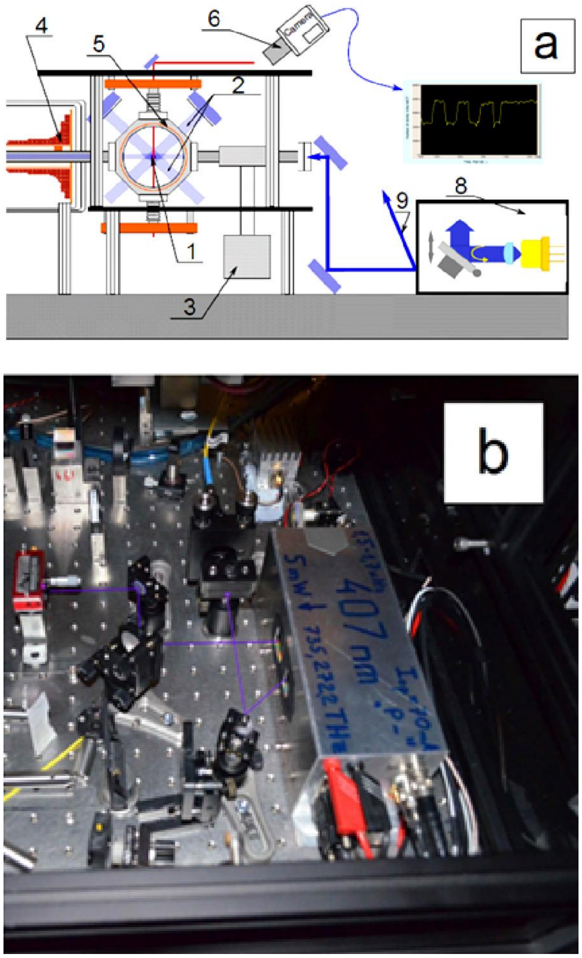

Fig.3. Sketch scheme of the experimental installation (a): (1-cloud of the atoms, 2-beams of the MOT, 3- vacuum pump, 4-coil of the Zeeman slower, 5-coils for creation of the magnetic field gradient in vacuum chamber, 6- digital camera for number of atoms registration, 7-repumping laser beam, 8-semiconductor laser with external cavity , Litrow scheme, 9-second beam of the diffraction grating, which was used for wavelength stabilization of the repumper laser) and view of the diode laser for singlet repumping on 407 nm (b).

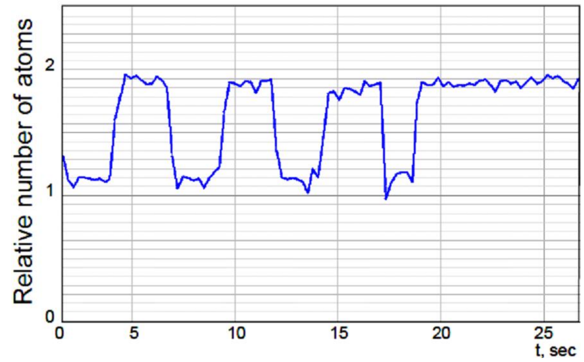

Fig.4. Plot of the number of MOT atoms in time. This plot was obtained from the state-of-the-art software for mentioned above digital camera Hamamatsu. It is clearly seen that detuning of the blue repumper laser from transition resonance and mechanical shutting lead to decreasing of the number of atoms down to initial value

Acknoledgments

Authors gratefully acknowledge for the invaluable help and collaboration with providing of the experimental installations Jerome Lodewyck, Rodolphe LeTargat from metrology laboratory ^{87}Sr optical lattice clocks at LNE-SYRTE, Paris Observatory.

Appendix A

Calculation of the populations without repumping laser.

$$\frac{dN_1}{dt} = R_1 - \left[L_{1,2}(N_1 - N_2) - \Gamma_{1,2}N_2\right] - \Gamma_{1,3P1}N_{3P1}, \quad (A.1)$$

$$\frac{dN_2}{dt} = \left[L_{1,2}(N_1 - N_2) - (\Gamma_{1,2}N_2 + \beta' N_2^2)\right] - \Gamma_{2,3}N_2, \quad (A.2)$$

$$\frac{dN_3}{dt} = \Gamma_{2,3}N_2 - \Gamma_{3,3P1}N_3 - \Gamma_{3,3P2}N_3, \quad (A.3)$$

$$\frac{dN_7}{dt} = \Gamma_{3,3P1}N_3 - \Gamma_{1,3P1}N_{3P1}, \quad (A.4)$$

where R_1- rate of loading of the trap, N_i – number of atoms in i^{th} level, $[Gamma]_{ij}$- spontaneous decay rate in i и j states, [15, 16].

Appendix B

Calculation of the populations with 407.72 nm repumping laser.

$$\frac{dN_1}{dt} = R_1 - \left[L_{1,2}(N_1 - N_2) - \Gamma_{1,2}N_2\right] + \Gamma_{1,3P1}N_{3P1} + \Gamma_{1,4}N_4, \quad (B.1)$$

$$\frac{dN_2}{dt} = \left[L_{1,2}(N_1 - N_2) - (\Gamma_{1,2}N_2 + \beta' N_2^2)\right] - \Gamma_{2,3}N_2, \quad (B.2)$$

$$\frac{dN_3}{dt} = -\left[L_{3,4}(N_3 - N_4) - \Gamma_{3,4}N_4\right] + \Gamma_{2,3}N_2 - \Gamma_{3,3P1}N_3 - \Gamma_{3,3P2}N_3, \quad (B.3)$$

$$\frac{dN_4}{dt} = \left[L_{3,4}(N_3 - N_4) - \Gamma_{3,4}N_4\right] - \Gamma_{4,3S1}N_4 - \Gamma_{2,4}N_4 - \Gamma_{1,4}N_4, \quad (B.4)$$

$$\frac{dN_{3P1}}{dt} = \Gamma_{3P1,3S0}N_{3S0} - \Gamma_{1,3P1}N_{3P1} + \Gamma_{3,3P1}N_3, \quad (B.5)$$

$$\frac{dN_{3S1}}{dt} = \Gamma_{4,3S1}N_{3S1} - \Gamma_{3P0,3S1}N_{3S1} - \Gamma_{7,3S1}N_{3S1} - \Gamma_{3P2,3S1}N_{3P2}, \quad (B.6)$$

Corresponding Author:
Dr.Gurov Mikhail Guennadievitch
Novosibirsk State Technical University
Av. K. Marx 20, Novosibirsk, 630073, Russia

References

1. Timothy, P., K. Dinneen, R. Vogel, A. Ennio, 1999. Cold collision of Sr*-Sr in a magneto-optical trap. Phys. Rev. A., 59: 1216-1222.
2. Xinye, Xu, H. Thomas, Loftus, J.L. Hall, 2003. Cooling and trapping of atomic strontium. J. Opt. Soc. Am. B., 5 (20): 968-976.
3. Mickelson, P.G., M. Escobar, P. Anzel, 2009. Repumping and spectroscopy of laser-cooled Sr atoms using the (5s5p)3P2-(5s4d)3D2 transition. Journal of Physics B: Atomic, Molecular and Optical Physics, 23(42): 235001.
4. Courtillot I., Q.Audrey, R.P. Kovacich, 2003. Clock transition for a future optical frequency standard with trapped atoms. Phys. Rev. A., 68: 3050.
5. Jonnson, G., C. Levinson, A.Persson, 1984. Zeitschrift Fur Physik A Hadrons and Nuclei, 1: 255-284.
6. Newsom, G.H., S. O'Connor, R.C.M. Learner, 1973. Re-examination of the spectrum of strontium: autoionization in the spectrum of neutral strontium. Journal of Physics B: Atomic and Molecular Physics, 10(6): 2162.
7. Rubbmark, J.R., S. Borgstrom, A. Rydberg, 1978. Absorption spectrum of Sr I between 1400 and 1900. Phys. Scr., 18: 196-208.
8. Sullivan, F.J., 1938. Strontium Lines in Arc and Solar Spectra. Univ. Pittsburgh. Bull, 35: 1-8.
9. Safronova, M.S., S.G. Porsev, U.I. Safronova, M.G. Kozlov, C.W. Clark, 2013. Blackbody-radiation shift in the Sr optical atomic clock. Phys. Rev. A, American Physical Society, 87: 012509.
10. Porsev, S.G., A.D. Ludlow, M.M. Boyd, J. Ye, 2008. Determination of Sr properties for a high-accuracy optical clock. Phys. Rev. A. American Physical Society, 78: 032508.
11. NIST. The NIST Reference on Constants, Units, and Uncertainty. Date Views 01.01.2014 www.physics.nist.gov/cuu/index.html.
12. Cable, A., M. Prentiss, N.P. Bigelow, 1990. Observations of sodium atoms in a magnetic molasses trap loaded by a continuous uncooled source Opt. Lett., OSA, 15: 507-509.
13. Kaczmarek, F., 1980. Introduction in laser Physics. M.: Mir, pp: 540.
14. Adams, C.S., E. Riis, 1997. Laser cooling and trapping of neutral atoms. Proc. Quant. Electr., 21:11-79.
15. Metcalf, H.J., P. Straten, 2003. Laser cooling and trapping of atoms J. Opt. Soc. Am. B, OSA, 20: 887-908.
16. Lett, P.D., W.D. Phillips, S.L. Rolston, 1989. Optical molasses. J. Opt. Soc. Am. B, OSA, 1989, 6: 2084-2107.

7/28/2014