Polarization dependence of two-photon excitation of cold $^7$Li Rydberg atoms

S A Saakyan, A A Bobrov, E V Vilshanskaya, V A Sautenkov and B B Zelener

Joint Institute for High Temperatures of the Russian Academy of Sciences, Izhorskaya 13 Bldg 2, Moscow 125412, Russia

E-mail: saasear@gmail.com

Abstract. The two-photon excitation of cold $^7$Li atoms at the $2S$–$120S$ transition is studied with variable polarization of one of the two counter-propagating optical beams. The maximum efficiency of the two-photon transfer of atoms from the ground state $2S$ to the Rydberg state $120S$ can be reached when the circular polarizations of the beams are orthogonal. In this case the selection rules $\Delta L = 0$ are satisfied. By using a rotating quarter-wave plate it is possible to vary the polarization of the selected optical beam and change the amplitude of the two-photon resonance. The recorded dependence of the two-photon resonance on the beam polarization is discussed. The obtained results can be used to compensate the unwanted variations of the beam polarization after reflections from mirrors.

1. Introduction

Two-photon Doppler-free spectroscopy was suggested in [1]. This spectroscopic method becomes widely used. The selection rules for two-photon transitions ($\Delta L = 0, \pm 2$) allow to study atomic states with the same parity. With the use of counter propagating beams with circular or linear polarization, it is possible to get narrow spectral resonances due to reduction of Doppler broadening. Also for two-photon excitation, it is easier to get available tunable lasers. These properties of the spectroscopic method open a way to investigate $2S$–$nS$ transitions in hydrogen-like atoms. This method was also used for two-photon spectroscopy of positronium [2].

Two-photon transitions are used to excite atoms and molecules in Rydberg states [3], to create qubits and perform research in the field of quantum informatics [4]. Recently a nondestructive technique for temperature measurements in magneto-optical trap (MOT) based on differential two-photon spectroscopy was suggested in [5]. In the present work we discuss our observations of two-photon $2S$–$120S$ excitation in $^7$Li obtained with the counter-propagating optical beams with variable polarization.

2. Experimental setup

The used energy levels in $^7$Li atom and the scheme of experimental setup are shown in figure 1. A detailed description of the experimental setup is presented in [6, 7].

The atoms in the MOT are excited to $120S$ state by two counter-propagating laser beams. The frequency of a “red” laser with a wavelength of 671 nm is detuned from the atomic transition $2S_{1/2}(F = 2)$ to $2P_{3/2}(F = 3)$ by interval 593 MHz. The polarization of the “red” beam is fixed.
and not changed during the measurements. After a quarter-wave plate ($\lambda/4$ in figure 1), the “red” beam has a circular polarization. In this case the axis of the wave plate is rotated at the angle $45^\circ$ from the direction of the electric field vector.

The polarization of uv laser beam can be varied. During measurements the frequency of uv laser is scanned near transition $2P_{3/2} - 120S$. In order to record the two-photon resonance we collect fluorescence of the lithium atoms trapped in the MOT. The wavelength of the uv laser is measured using wave-meter Angstrom WSU.

The experimental technique is described in [8]. A detailed description of the uv laser system and stabilization unit is given in [9].

3. Results

For $S-S$ transitions, the selection rules are $\Delta L = 0$. Maximum of the two-photon resonance is observed when both laser beams are linear polarized or orthogonally circularly polarized. We obtain two-photon excitation spectra of lithium atoms in MOT for different polarizations of the uv laser beam.

In figure 2, the resonances on the $2S-120S$ transition are shown. The frequency of uv laser is scanned around the Rydberg transition. The maximum amplitude is observed when the polarization of the uv beam $\sigma^+$ is orthogonal to the polarization of “red” beam $\sigma^-$ (the QWP for uv beam is in position when the angle is of $-45^\circ$). Further rotation of QWP leads to a decrease in the amplitude of the observed resonance which is shown in figure 2(b).

The amplitude dependence of two–photon resonances on the angle of the uv beam QWP are presented in figure 3. The dependence is well approximated by a sinusoidal function with phase shift $12^\circ$. The polarization of the red beam is close to circular $\sigma^-$. Reflection from the dielectric mirror introduces a phase shift in the polarization of the red beam. In figure 3(b), the dashed line shows the same dependence with the phase equal to zero.
Figure 2. The two-photon resonance corresponding Rydberg state $120S$: solid curve is the observed resonance for the $\sigma^+$ polarization of uv laser beam with QWP angle 45° $(a)$ and the elliptical polarization of uv laser beam with QWP angle 82.5° $(b)$; dashed curve is the result of fitting experimental data by Gaussian function with full width at half maximum (FWHM) of 10 $(a)$ and 9 MHz $(b)$.

Figure 3. Dependence of the amplitude of two-photon resonances on the angle of the uv beam QWP $(a)$ and the same dependence in polar scale $(b)$: black squares are experimental data; solid line is the fit by sine function with phase shift 12°; dash line is theoretical curve with zero phase shift; blue squares are mirror reflection of experimental points with respect to the horizontal axis.

4. Conclusions
The two-photon $2S$–$120S$ transition is allowed when atomic angular moment is constant $\Delta L = 0$. This selection rule can be satisfied with counter-propagating orthogonal circular polarized beams
or linear polarized beams. By using quarter-wave plate we can vary the polarization of one of the optical beam (uv) and change the amplitude of the two-photon resonance from maximum ($\sigma^+ \sigma^-$) to minimum ($\sigma^+ \sigma^+ or \sigma^- \sigma^-$). Intermediate signal corresponds to the linear polarization of the uv beam. The linear polarized optical field is linear superposition of two circularly polarized fields. It is shown that the beam reflected from the dielectric mirror demonstrates a small change of its polarization. All results are good agreement with theory.

Acknowledgments
This work was supported by the Russian Science Foundation under project No. 14-50-00124.

References
[1] Vasilenko L S, Chebotaev V P and Shishaev A V 1970 JETP Lett. 12 113–6
[2] Fee M S, Chu S, Mills Jr A P, Chichester R J, Zuckerman D M, Shaw E D and Danzmann K 1993 Phys. Rev. A 48 192–219
[3] Wilk T, Gaëtan A, Evellin C, Wolters J, Miroshnychenko Y, Grangier P and Browaeys A 2010 Phys. Rev. Lett. 104 010502
[4] Bernien H, Schwartz S, Keesling A, Levine H, Omran A, Pichler H, Lukin M and Vuletic V 2017 Nature 551 579–84
[5] Sautenkov V A, Saakyan S A, Vilshanskaya E V, Zelener B B and Zelener B V 2017 J. Russ. Laser Res. 38 91–5
[6] Zelener B B, Saakyan S A, Sautenkov V A, Akulshin A M, Manykin E A, Zelener B V and Fortov V E 2014 JETP Lett. 98 670–4
[7] Zelener B B, Saakyan S A, Sautenkov V A, Manykin E A, Zelener B V and Fortov V E 2014 J. Exp. Theor. Phys. 119 795–801
[8] Saakyan S A, Sautenkov V A, Vilshanskaya E V, Vasiliev V V, Zelener B B and Zelener B V 2015 Quantum Electron. 45 828–32
[9] Saakyan S A, Sautenkov V A and Zelener B B 2018 J. Phys.: Conf. Ser. 946 012128