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Efficient Excitation of Rydberg States in Ultracold Lithium-7 Atoms

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This work is aimed at preparing highly excited optically cooled lithium-7 atoms for producing a strongly nonideal plasma and Rydberg matter. A setup implementing a novel nondestructive technique for preparation and diagnostics of highly excited Rydberg atomic states is constructed. The operation of this setup is based on the usage of a cw high-power ultraviolet laser combined with a magneto-optical trap. The diagnostics of highly excited states is performed by the direct recording of the variations in the fluorescence of ultracold lithium-7 atoms in the magneto-optical trap.

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1. INTRODUCTION

The studies of the systems consisting of highly excited Rydberg atoms are of appreciable current interest because of the possibility of modeling the processes related to astrophysics and quantum computing, as well as of creating antimatter. The ability to control the processes of decay and crystallization could be fundamental for developing quantum computers [1]. This idea resulted in experiments on the interactions with individual Rydberg atoms and their blockade [2–4]. The experiments with Rydberg atoms can become the model ones for studies on the recombination behavior characteristic of the experiments involving the creation of antihydrogen [5–7]. They can also be helpful in the search for optimum ways for the trapping of a large amount of antihydrogen atoms by using high applied magnetic fields. Note that lithium is a chemical element closest in its characteristics to hydrogen.

This paper extends a series of our experimental and theoretical works dealing with producing and studying the ensembles of ultracold Rydberg atoms [8–13]. There are a sufficiently large number of works concerning the preparation and diagnostics of highly excited Rydberg states. These studies involve both clouds of ultracold atoms and pencil beams of hot atoms. One of the ways for generating such states is their pulsed multistage excitation with the further diagnostics using the emission of electrons induced by a weak dc electric field [14–16]. A disadvantage of such methods is a small number of excited atoms and the destruction of Rydberg states resulting from the diagnostics. In the experiments reported in [17], the diagnostics of Rydberg atoms was implemented through the use of the weak probe field related to the resonant transition and the high controlling field related to the transitions between the excited states. The electromagnetically induced transparency was recorded in the probe field spectrum. In these experiments, the population of the Rydberg states was also quite low. In our setup, we implement the method of coherent excitation of the Rydberg states. The possibility of its implementation in the cascade system of the low-lying $5S$–$5P$–$5D$ levels was described in [18]. A specific feature of this method is the process targeted at the two-photon excitation of the Rydberg levels involving the intermediate atomic state. Note that this process is highly efficient. At a sufficient laser power, the majority of atoms located within the magneto-optical trap are transferred to the Rydberg state during a short time interval in the continuous coherent two-photon process.

2. EXPERIMENTAL SETUP

In our experiments, we use lithium-7 atoms. To produce ultracold gas of highly excited (Rydberg) lithium atoms and ultracold plasma consisting of lithium atoms, we developed an experimental setup. This setup provides an opportunity to perform the laser-induced cooling of lithium atoms and their reliable confinement within the magneto-optical trap at an

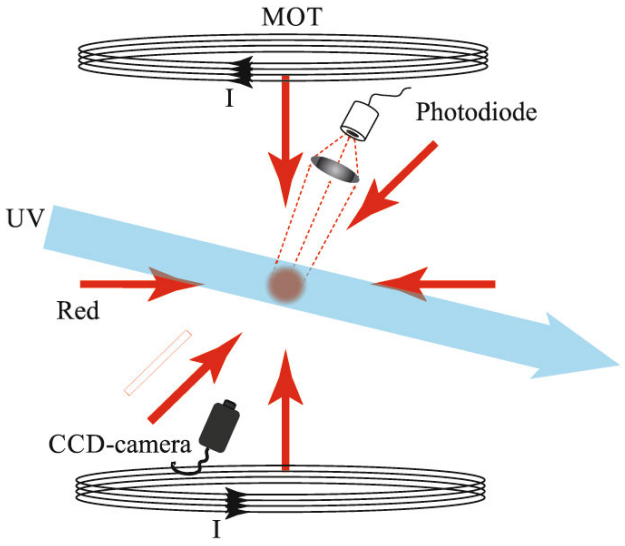

Fig. 1. (Color online) Schematic diagram of the setup for generation of Rydberg atoms using lithium-7 atoms confined within the magneto-optical trap.

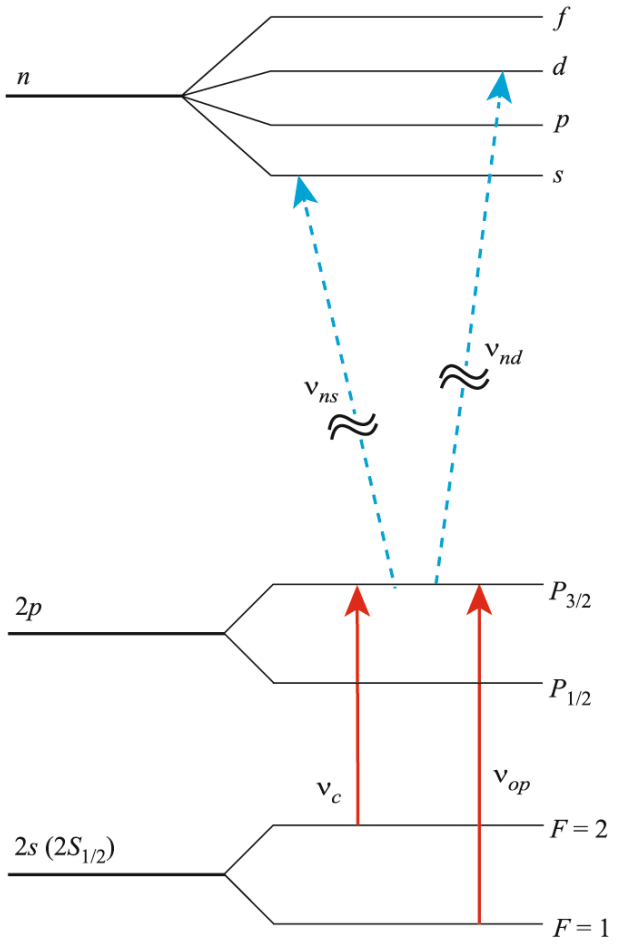

Fig. 2. (Color online) Diagram of levels in lithium-7 atoms.

ultralow temperature [12, 13]. A schematic diagram of the performed experiment is shown in Fig. 1.

For producing Rydberg atoms, we use a cw ultraviolet (UV) laser (Newport-Spectra Physics). The laser operates in the free generation mode. This laser with an output power up to 100 mW works at a wavelength of 350 nm and has a width of the emitted radiation spectrum of the order of several megahertz. The UV laser radiation is directed to the cloud of ultracold atoms located within the trap and the radiation frequency is continuously tuned. When the UV laser frequency passes through the resonance with the Rydberg transition, we observe the reduction of the fluorescence of the atomic cloud down to its partial or complete vanishing depending on the UV laser power and on the upper level involved in the transition. After passing through the resonance, ultracold atoms start again to be accumulated within the magneto-optical trap. For the reliable recording and determination of the transition frequency, in addition to the recording by the CCD camera, we use a photodetector, onto which a certain portion of the fluorescence is focused by a lens. The UV laser frequency is controlled by a high-precision wavelength meter WS-U (High Finesse-Angstrom). In our experiment, the wavelength meter is calibrated using a stabilized diode laser operating at a wavelength of 780 nm, whose frequency is stabilized by a cell with rubidium-85 vapor within the saturated spectrometry scheme. The diagram depicting the levels involved in the transitions into the Rydberg states is shown in Fig. 2.

According to the selection rules, the transitions from the $2P$ state are possible only to the nS and nD states, whereas the probability of the transition to the D level is higher than that to the S level. The detuning of the cooling laser is 46 MHz and the detuning of the optical pumping laser is 20 MHz toward the red side from the resonance for achieving the density of ultracold atoms equal to about 5×10^{10} cm^{-3} [12, 13].

3. EXPERIMENTAL RESULTS

We studied several transitions from the low-lying $2P_{3/2}$ state to the highly excited S and D Rydberg states. In Fig. 3, we illustrate the results obtained for the transitions to the $41S$ and $41D$ states.

On the vertical axis, zero corresponds to the complete absence of the fluorescence from the cloud of cold atoms, whereas unity corresponds to the maximum fluorescence signal from the cloud, when the cloud turns out to be transparent to the UV laser radiation. The scanning range of the UV laser does not allow observing simultaneously both the transitions to the $41S$ and $41D$ states. For this reason, in Fig. 3, we show the results of two measurements shifted in time. The labels on the lower horizontal axis denote the relative interlevel distance in gigahertz, whereas the

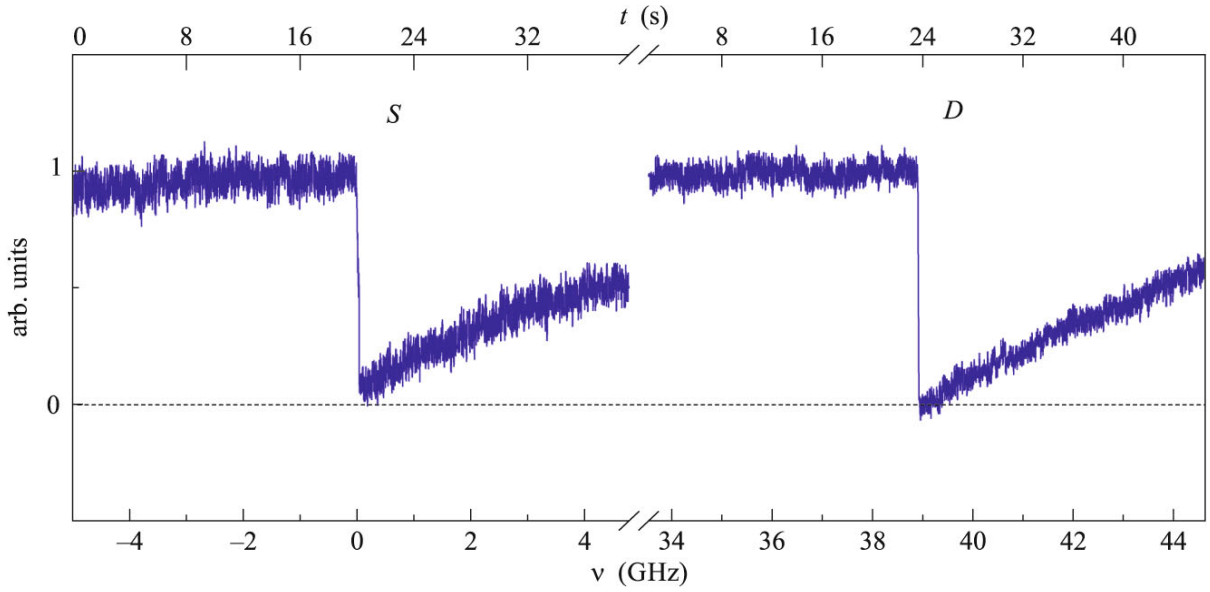

Fig. 3. (Color online) Variation of the fluorescence from a cloud of ultracold atoms corresponding to the 41st level in S and D states at the input intensity of UV radiation equal to 8.5×10^{-3} W/cm^2 at the entrance to the vacuum chamber.

labels on the upper one denote time (in seconds) during which the laser frequency is being changed.

To evaluate the results, we used the information on Li-7 from the NIST database. In this database, one can find the data corresponding to Li-7 levels only to the 42nd one and only for the transition from the S to P state. Since the tuning range for our cw UV laser does not allow the excitation of Li-7 atoms with $n < 40$, we use for comparison the data from [19] concerning $n = 41$ obtained for the transition from the ground S to the Rydberg P state. Our experimental data for $n = 41$ and $n = 94$ at the transitions from the P state to S and D states are given in Table 1.

Taking the ionization threshold frequency ν_i [14] and the frequency ν_C of the cooling laser [20], we can calculate the principal quantum number taking into account the quantum defect (Table 1) by the formula

$$n = \sqrt{\frac{R_\mathrm{H}}{\nu_i - \nu_C - \nu_n}}.$$

For the 41st P level from the NIST database, we have

$$n = \sqrt{\frac{R_\mathrm{H}}{\nu_i - \nu_{41P}}}.$$

The values used in the calculation are given in Table 2.

In Table 1, we see that the 41S level lies above (in the wavelength scale) the 41P level, while the 41D level lies below it. In addition, the 41D level is characterized by the smallest quantum defect related to the difference between lithium-7 and hydrogen atoms [22]. In Fig. 4, we demonstrate the experimental results for the 94th level concerning the transitions to the S and D states at different levels of the power generated by the UV laser.

The quenching time for the cloud of atoms excited to the 94th level is much longer than that for the 41st level and the quenching level is much lower. For the 94th level, the relative experimental error is an order of magnitude larger than that for the 41st level. We also

Table 1. Data for high Rydberg levels of lithium-7*

Notation of ν_n	Transition, cm^{-1}	Usual notation for transitions	Transition, nm	n, calculated in comparison to hydrogen
ν_{41S}	28516.61(1)	$1s^2 2p_{3/2}(F=2)-1s^2 41s$	350.6728(1)	40.600(2)
ν_{41P} (NIST)	43420.9	$1s^2 2s-1s^2 41p$		40.7
ν_{41D}	28517.90(1)	$1s^2 2p_{3/2}(F=2)-1s^2 41d$	350.6569(1)	41.000(2)
ν_{94S}	28570.6(1)	$1s^2 2p_{3/2}(F=2)-1s^2 41s$	350.010(1)	93.4(3)
ν_{94D}	28570.8(1)	$1s^2 2p_{3/2}(F=2)-1s^2 41d$	350.008(1)	94.0(3)

* Notation 41.000(2) corresponds to 41.000 ± 0.002.

Table 2. Exact values of the Rydberg constant, cooling transition, and ionization threshold for lithium-7 atoms

Notation	Transition, cm^{-1}	Usual notation for transitions
R_H	109737, 31568516(84) [21]	Rydberg constant for hydrogen
ν_C	14903.9730012	$1s^2 2s_{1/2}(F=2)-1s^2 2p_{3/2}$
ν_i	43487.1594(2)	$1s^2 2s-\infty$

observe an appreciable difference in intensity between the S and D levels. The amount of created Rydberg atoms can be controlled by increasing or decreasing the UV laser power.

4. CONCLUSIONS

As a result of this study, we have developed an efficient technique to detect the states of Rydberg atoms. It is based on the usage of a cw UV laser combined with a magneto-optical trap for lithium-7 atoms. We have studied the 41st and 94th states of S and D configurations in ultracold lithium-7 atoms. Our experimental data verify that the principal quantum numbers for 41D and 94D configurations in lithium-7 atoms coincide within the experimental error with those characterizing the 41st and 94th levels in hydrogen atoms. The difference in the principal quantum numbers for 41S and 94S configurations in lithium atoms is determined taking into account the quantum defect. The main advantage of the used experimental setup is the possibility to detect the Rydberg states avoiding the destruction of Rydberg atoms. The atoms have a very low temperature. Therefore, the Doppler broadening does not manifest itself. Further studies can result in a significant enhancement in the accuracy of measurements. The implemented design of the experimental setup is similar to that of a reliable 0–1 logic element. This technique also allows creating a large number of Rydberg atoms by the efficient two-stage coherent process with the aim to generate strongly nonideal ultracold plasma [23] and Rydberg matter (crystallization of Rydberg atoms) [24–28].

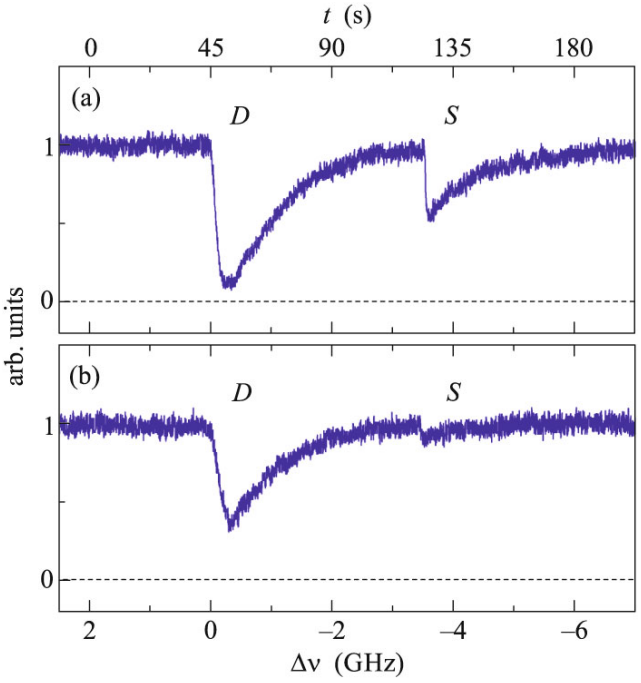

Fig. 4. (Color online) Variation of the fluorescence from a cloud of ultracold atoms corresponding to the 94th level in S and D states at the input intensity of UV radiation equal to (a) 6.1×10^{-3} and (b) 0.8×10^{-3} W/cm^2 at the entrance to the vacuum chamber.

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REFERENCES

1. R. P. Feynman, Int. J. Theor. Phys. **21**, 467 (1982).
2. M. Viteau, M. G. Bason, J. Radogostowicz, N. Malossi, D. Ciampini, O. Morsch, and E. Arimondo, Phys. Rev. Lett. **107**, 060402 (2011).
3. E. Urban, T. A. Johnson, T. Henage, L. Isenhower, D. D. Yavuz, T. G. Walker, and M. Saffman, Nature Phys. **5**, 110 (2009).
4. D. B. Tretyakov, V. M. Entin, E. A. Yakshina, I. I. Beterov, Ch. Andreeva, and I. I. Ryabtsev, arXiv:1404.0438 (2014).
5. M. Amoretti et al. (ATHENA Collab.), Phys. Lett. B **23**, 578 (2004).

6. G. Gabrielse et al. (ATRAP Collab.), Phys. Rev. Lett. **89**, 233401 (2002).
7. G. B. Andresen et al. (ALPHA Collab.), Nature Phys. **7**, 558 (2011).
8. A. A. Bobrov, S. Ya. Bronin, B. B. Zelener, B. V. Zelener, E. A. Manykin, and D. R. Khikhlukha, J. Exp. Theor. Phys. **112**, 527 (2011).
9. S. Ya. Bronin, B. B. Zelener, B. V. Zelener, E. A. Manykin, and D. R. Khikhlukha, J. Exp. Theor. Phys. **112**, 717 (2011).
10. B. B. Zelener, B. V. Zelener, and E. A. Manykin, JETP Lett. **94**, 525 (2011).
11. A. A. Bobrov, S. Ya. Bronin, B. B. Zelener, E. A. Manykin, and D. R. Khikhlukha, J. Exp. Theor. Phys. **117**, 161 (2013).
12. B. B. Zelener, S. A. Saakyan, V. A. Sautenkov, A. M. Akul'shin, E. A. Manykin, B. V. Zelener, and V. E. Fortov, JETP Lett. **98**, 670 (2013).
13. B. B. Zelener, S. A. Saakyan, V. A. Sautenkov, E. A. Manykin, B. V. Zelener, and V. E. Fortov, Zh. Eksp. Teor. Fiz. **146** (11) (2014, in press).
14. B. A. Bushaw, W. Nörtershäuser, G. W. F. Drake, and H.-J. Kluge, Phys. Rev. A **75**, 052503 (2007).
15. S. Ye, X. Zhang, T. C. Killian, F. B. Dunning, M. Hiller, S. Yoshida, S. Nagele, and J. Burgdorfer, Phys. Rev. A **88**, 043430 (2013).
16. T. F. Gallagher, *Rydberg Atoms* (Cambridge Univ. Press, Cambridge, 1994).
17. A. K. Mohapatra, T. R. Jackson, and C. S. Adams, Phys. Rev. Lett. **98**, 113003 (2007).
18. A. S. Zibrov, M. D. Lukin, L. Hollberg, and M. O. Scully, Phys. Rev. A **65**, 051801 (2002).
19. A. Kramida, Yu. Ralchenko, J. Reader, http://physics.nist.gov/asd (2013).
20. C. J. Sansonetti, C. E. Simien, J. D. Gillaspy, J. N. Tan, S. M. Brewer, R. C. Brown, S. Wu, and J. V. Porto, Phys. Rev. Lett. **107**, 023001 (2011).
21. C. Schwob, L. Jozefowski, B. de Beauvoir, L. Hilico, F. Nez, L. Julien, F. Biraben, O. Acef, J.-J. Zondy, and A. Clairon, Phys. Rev. Lett. **82**, 4960 (1999).
22. I. I. Sobel'man, *Introduction to the Theory of Atomic Spectra* (Nauka, Moscow, 1977) [in Russian].
23. T. C. Killian, M. J. Lim, S. Kulin, R. Dumke, S. D. Bergeson, and S. L. Rolston, Phys. Rev. Lett. **86**, 3759 (2001).
24. E. A. Manykin, M. I. Ozhovan, and P. P. Poluektov, Sov. Phys. Dokl. **26**, 974 (1981).
25. E. A. Manykin, M. I. Ozhovan, and P. P. Poluektov, Sov. Phys. JETP **75**, 440 (1992).
26. T. Pohl, E. Demler, and M. D. Lukin, Phys. Rev. Lett. **104**, 043002 (2010).
27. T. Pohl, C. S. Adams, and H. R. Sadephpour, J. Phys. B: At. Mol. Opt. Phys. **44**, 180201 (2011).
28. P. Schauß, M. Cheneau, M. Endres, T. Fukuhara, T. Fukuhara, S. Hild, A. Omran, Th. Pohl, Ch. Gross, S. Kuhr, and I. I. Bloch, Nature **491**, 87 (2012).

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