



AFRL-AFOSR-VA-TR-2024-0006

STRUCTURE & DYNAMICS OF EXCITED ATOMS

Gallagher, Thomas
UNIVERSITY OF VIRGINIA
1001 N EMMET ST
CHARLOTTESVILLE, VA,
US

10/05/2023
Final Technical Report

DISTRIBUTION A: Distribution approved for public release.

Air Force Research Laboratory
Air Force Office of Scientific Research
Arlington, Virginia 22203
Air Force Materiel Command

REPORT DOCUMENTATION PAGE

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.

| | | | | | |
|--|-------------------------|---|--|--|---|
| 1. REPORT DATE 20231005 | | 2. REPORT TYPE Final | | 3. DATES COVERED | |
| | | | | START DATE 20140801 | END DATE 20200731 |
| 4. TITLE AND SUBTITLE STRUCTURE & DYNAMICS OF EXCITED ATOMS | | | | | |
| 5a. CONTRACT NUMBER | | 5b. GRANT NUMBER FA9550-14-1-0288 | | 5c. PROGRAM ELEMENT NUMBER 61102F | |
| 5d. PROJECT NUMBER | | 5e. TASK NUMBER | | 5f. WORK UNIT NUMBER | |
| 6. AUTHOR(S) Thomas Gallagher | | | | | |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) UNIVERSITY OF VIRGINIA 1001 N EMMET ST CHARLOTTESVILLE, VA US | | | | 8. PERFORMING ORGANIZATION REPORT NUMBER | |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Air Force Office of Scientific Research 875 N. Randolph St. Room 3112 Arlington, VA 22203 | | | 10. SPONSOR/MONITOR'S ACRONYM(S) AFRL/AFOSR RTB1 | | 11. SPONSOR/MONITOR'S REPORT NUMBER(S) AFRL-AFOSR-VA-TR-2024-0006 |
| 12. DISTRIBUTION/AVAILABILITY STATEMENT A Distribution Unlimited: PB Public Release | | | | | |
| 13. SUPPLEMENTARY NOTES | | | | | |
| 14. ABSTRACT During the grant period we focused on the use of microwaves to manipulate and probe interacting atoms. Cold Rydberg atoms in a magneto optical trap (MOT) are randomly spaced, leading to a large variation in the dipole-dipole interaction strength, and, in general, cusp shaped energy transfer resonances. We demonstrated that driving one microwave transition, for example $ns-(n-1)p$, we could remove ns atoms with selected spacings, allowing the $ns-n'p$ to be observed without the deselected atoms. Removing widely spaced ns atoms results in a Lorentzian lineshape. 3 | | | | | |
| 15. SUBJECT TERMS | | | | | |
| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT UU | | 18. NUMBER OF PAGES 4 |
| a. REPORT U | b. ABSTRACT U | c. THIS PAGE U | | | |
| 19a. NAME OF RESPONSIBLE PERSON GRACE METCALFE | | | | 19b. PHONE NUMBER (Include area code) (703) 696-9740 | |

Standard Form 298 (Rev. 5/2020)
Prescribed by ANSI Std. Z39.18

Structure and Dynamics of Excited Atoms

AFOSR grant FA9550-14-1-0288

3 May 2014 to 31 July 2019

Final Report

Prepared for

Dr. Grace Metcalfe

Thomas F. Gallagher

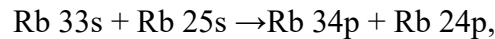
Department of Physics

University of Virginia

Charlottesville, Virginia 22904

The Air Force Office of Scientific Research (AFOSR) grant “Structure and Dynamics of Excited Atoms,” grant FA9550-14-1-0288, covered the period 3 May 2014-31 July 2019. The papers resulting from this grant are listed in the appendix, and a brief summary of the research undertaken follows.

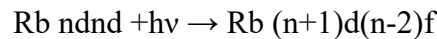
The effort during the grant period was focused on the interactions between cold Rydberg atoms, a topic which is currently being explored in many laboratories. Investigations with cold Rydberg atoms began with Forster resonant energy transfer experiments at Laboratoire Aime Cotton in France and at the University of Virginia with the support of AFOSR.^{1,2} At the University of Virginia we observed the resonant dipole-dipole energy transfer



which is tuned into resonance with a small, 3 V/cm, field.

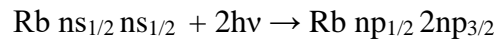
During the grant period we focused on the use of microwaves to manipulate and probe interacting atoms. Cold Rydberg atoms in a magneto optical trap (MOT) are randomly spaced, leading to a large variation in the dipole-dipole interaction strength, and, in general, cusp shaped energy transfer resonances. We demonstrated that driving one microwave transition, for example $ns-(n-1)p$, we could remove ns atoms with selected spacings, allowing the $ns-n'p$ to be observed without the deselected atoms. Removing widely spaced ns atoms results in a Lorentzian lineshape.³

Most of our effort in this grant period went into the study of microwave transitions of pairs of atoms.^{3-7,9} An example is the transition



Here the two interacting atoms are described as a molecular state. Although both atoms change state, only one microwave photon is absorbed. This process occurs because the dipole-dipole interaction admixes a small amount of the $\text{Rb } (n+2)p(n-2)f$ state into the $ndnd$ state. We have observed transitions in which up to three microwave photons are absorbed, and we have developed a description of these processes as Forster resonances of Floquet states. While the tuning in the initial Forster resonance experiments was done using a static field, in these measurements it is accomplished by tuning the microwave frequency.

A particularly interesting microwave transition is the case^{7,9}



It was not obvious that it would be observable since many of the transition amplitudes cancel. For example, if no change in the azimuthal angular momentum quantum number m_j is allowed, the transition is theoretically impossible. However, in our cold Rydberg atom sample the internuclear axes and the microwave field are not aligned but at random angles, so changes in m_j occur, and the transition is observed. This process has an extremely high principal quantum number n dependence, n^{14} , which we have verified experimentally.

By accident we realized that we could do two photon excitation from the Rb 5p state to the nf state, using one optical photon and one microwave photon.⁸ With small, up to 2 GHz, detuning of the laser from the Rb 5p-nd transition only milliwatts of microwave power are required. This approach allows efficient population of a higher angular momentum Rydberg state without any population in a low angular momentum Rydberg state.

References

1. I. Mourachko, D. Comparat, F. de Tomasi, A. Fioretti, P. Nosbaum, V. Akulin, and P. Pillet, *Physical Review Letters* **80**, 253 (1998).
2. W. R. Anderson, J. A. Veale, and T. F. Gallagher, *Physical Review Letters* **80**, 249 (1998).
3. H. Park, T. F. Gallagher, and P. Pillet, *Physical Review A* **93**, 052501 (2016).
4. J. Lee and T. F. Gallagher, *Physical Review A* **93**, 062509 (2016).
5. J. Lee, J. Nunkaew, and T. F. Gallagher, *Physical Review A* **94**, 022505 (2016).
6. J. Lee, J. Iqbal, and T. F. Gallagher, *Physical Review A* **96**, 012507 (2017).
7. J. Lee, P. Kongkambut, and T. F. Gallagher, *Physical Review A* **96**, 061401 (2017).
8. D. A. Tate and T. F. Gallagher, *Physical Review A* **94**, 022505 (2016).
9. J. Nunkaew, R. Ali, and T. F. Gallagher, *Physical Review A* **102**, 023332 (2020).
10. S. J. Berl, C. A. Sacket, T. F. Gallagher, and J. Nunkaew, *Physical Review A* **102**, 062818 (2020).

Appendix: Publications resulting from grant FA9550-14-1-0288

1. H. Park, T. F. Gallagher, and P. Pillet, “Microwave pump-probe spectroscopy of the dipole-dipole interaction in a cold Rydberg gas,” *Physical Review A* **93**, 052501 (2016).
2. J. Lee and T. F. Gallagher, “Microwave transitions from pairs of Rb $nd_{5/2}nd_{5/2}$ atoms,” *Physical Review A* **93**, 062509 (2016).
3. J. Lee, J. Nunkaew, and T. F. Gallagher, “Microwave spectroscopy of the cold Rb $(n+1)d_{5/2} \rightarrow ng$, and nh transitions,” *Physical Review A* **94**, 022505 (2016).
4. J. Lee, J. Iqbal, and T. F. Gallagher, “Microwave transitions in pairs of cold Rb Rydberg atoms,” *Physical Review A* **96**, 012507 (2017).
5. J. Lee, P. Kongkambut, and T. F. Gallagher, “Excitonlike exchange in two photon transitions in pairs of cold Rb Rydberg atoms,” *Physical Review A* **96**, 061401 (2017).
6. D. A. Tate and T. F. Gallagher, “Microwave optical two photon excitation of Rydberg states,” *Physical Review A* **94**, 022505 (2016).
7. J. Nunkaew, R. Ali, and T. F. Gallagher, “Resonant energy transfer Rb $ns+Rb\ ns+2h\nu \rightarrow Rb\ np_{1/2}+Rb\ np_{3/2}$ in a frozen Rydberg gas,” *Physical Review A* **102**, 023332 (2020).
8. S. J. Berl, C. A. Sacket, T. F. Gallagher, and J. Nunkaew, “Core polarizability of rubidium using spectroscopy of the ng to nh , ni transitions,” *Physical Review A* **102**, 062818 (2020).

