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14. ABSTRACT

15. SUBJECT TERMS

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a. REPORT UU	b. ABSTRACT UU	c. THIS PAGE UU	19b. TELEPHONE NUMBER 740-587-8661

RPPR Final Report
as of 21-Mar-2018

Agency Code:

Proposal Number: 64480PH

Agreement Number: W911NF-13-1-0410

INVESTIGATOR(S):

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Report Date: 25-Feb-2018

Date Received: 24-Feb-2018

Final Report for Period Beginning 26-Aug-2013 and Ending 25-Nov-2017

Title: Laser Cooling Trapped Ions With Telecom Light For Applications in Quantum Information.

Begin Performance Period: 26-Aug-2013

End Performance Period: 25-Nov-2017

Report Term: 0-Other

Submitted By: Steven Olmschenk

Email: steven.olmschenk@denison.edu

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Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 10

STEM Participants: 11

Major Goals: The main objectives of this project were to (1) measure the hyperfine energy splitting of the ground and first excited states of doubly-ionized lanthanum, and (2) to demonstrate laser cooling and trapping of doubly-ionized lanthanum.

Accomplishments: Please see uploaded PDF.

RPPR Final Report as of 21-Mar-2018

Training Opportunities: **Training**

Undergraduate students involved in this research received training from the PI on technical aspects of the project. This technical training included: lasers; optics; fiber-optics; mechanical design, including 3D CAD with Autodesk Inventor; and electronic design, including PCB fabrication with Eagle. Students also received additional training in aspects of atomic physics, including: trapping of charged particles; laser cooling; optical pumping; quantum information; and spectroscopy.

During this period supported by this grant, the undergraduate students involved with the project were:

- Patrick Banner (class of 2018);
- Jessica Hankes (class of 2017);
- Amanda Nelson (class of 2017);
- Patrick Becker (class of 2016);
- Edward (Zach) Pewitt (class of 2016);
- Elizabeth Donoghue (class of 2015);
- Kristina Dungan (class of 2015);
- Dongwei (Jackie) Liu (class of 2015);
- Bradley Bedacht (class of 2014);
- Nick Theisen (class of 2014);
- Eric Meier (class of 2014).

****Professional development****

Professional development activities for the students listed above during the period supported by this grant included:

- APS Division of Atomic, Molecular, and Optical Physics (DAMOP) conference (Sacramento, CA; June 2017):
Jessica Hankes, Amanda Nelson, and Patrick Banner;
- Optics and Photonics Winter School and Workshop (Tucson, Arizona; Jan. 2017): Jessica Hankes;
- APS Division of Atomic, Molecular, and Optical Physics (DAMOP) conference (Columbus, OH; June 2015):
Patrick Becker and Kristina Dungan;
- Midwest Cold Atom Workshop (West Lafayette, IN; November 2013): Bradley Bedacht and Nick Theisen.

Professional development activities for the PI during the period supported by this grant included:

- APS Division of Atomic, Molecular, and Optical Physics (DAMOP) conference (Sacramento, CA; June 2017);
- ARO Program Review (Cocoa Beach, FL; June 2017);
- Optics and Photonics Workshop (Tucson, AZ; Jan. 2017);
- Southwest Quantum Information and Technology (SQInT) Workshop (Albuquerque, NM; February 2016);
- Midwest Cold Atom Workshop (Madison, WI; November 2015);
- APS Division of Atomic, Molecular, and Optical Physics (DAMOP) conference (Columbus, OH; June 2015);
- Quantum Science Gordon Research Conference (Easton, MA; July 2014);
- APS Division of Atomic, Molecular, and Optical Physics (DAMOP) conference (Madison, WI; June 2014);
- Midwest Cold Atom Workshop (West Lafayette, IN; November 2013): Bradley Bedacht and Nick Theisen.

RPPR Final Report as of 21-Mar-2018

Results Dissemination: **Dissemination**

Professional dissemination:

- June 2017, APS Division of Atomic, Molecular, and Optical Physics (DAMOP) conference, Sacramento, CA, "Toward laser cooling and trapping lanthanum ions" (Presentation);
- June 2017, APS Division of Atomic, Molecular, and Optical Physics (DAMOP) conference, Sacramento, CA, "Towards trapping and laser cooling Ba and La ions" (Poster; presented by students);
- June 2017, APS Division of Atomic, Molecular, and Optical Physics (DAMOP) conference, Sacramento, CA, "Optogalvanic spectroscopy of lanthanum hyperfine structure" (Poster; presented by students);
- June 2017, ARO Program Review, Cocoa Beach, FL, "Laser cooling trapped ions with telecom light for applications in quantum information" (Presentation).
- May 2017, Atomic Physics Seminar at The Ohio State University, Columbus, OH, "Ions and Photons for Quantum Information";
- January 2017, Optics and Photonics Workshop, Tucson, AZ, "Ions and Photons for Quantum Information" (Invited Presentation);
- January 2017, Optics and Photonics Workshop, Tucson, AZ, "Optogalvanic Spectroscopy of La I Hyperfine Structure" (Poster; presented by students);
- February 2016, Southwest Quantum Information and Technology (SQuInT) Workshop, Albuquerque, NM, "Towards Laser Cooling of Trapped Ions with Telecom Light" (Poster);
- November 2015, Midwest Cold Atom Workshop (MCAW), Madison, WI, "Towards Laser Cooling of Trapped Ions with Telecom Light" (Poster);
- June 2015, APS Division of Atomic, Molecular, and Optical Physics (DAMOP) conference, Columbus, OH, "Towards Laser Cooling Trapped Ions with Telecom Light" (Poster; presented by students);
- June 2015, APS Division of Atomic, Molecular, and Optical Physics (DAMOP) conference, Columbus, OH, "La Saturated Absorption Spectroscopy for Applications in Quantum Information" (Poster; presented by students);
- July 2014, Quantum Science Gordon Research Conference, Easton, MA, "Towards Laser Cooling Ions with Telecom Light" (Poster);
- June 2014, APS Division of Atomic, Molecular, and Optical Physics (DAMOP) conference, Madison, WI, "Towards Laser Cooling Ions with Telecom Light" (Poster);
- November 2013, Midwest Cold Atom Workshop (MCAW), West Lafayette, IN, "Towards Quantum Information with Ions and Telecom Photons" (Poster; presented by students);

Outreach/public dissemination:

- December 2017, Physics Department colloquium at Williams College (a small liberal arts college), Williamstown, MA, "Quantum Information with Atoms and Light";
- April 2017, Physics Department colloquium at Amherst College (a small liberal arts college), Amherst, MA, "Ions and Photons for Quantum Information";
- April 2017, Physics Department colloquium at Smith College (a small liberal arts college), Northampton, MA, "Ions and Photons for Quantum Information";
- March 2017, Faculty Research Dinner at Denison University (presentation to an audience comprised mostly of non-scientists), Granville, OH, "Lasers, Atoms, and Bits";
- February 2016, Physics Department colloquium at the College of Wooster (a small liberal arts college), Wooster, OH, "Quantum Information with Ions and Photons";
- April 2015, Physics Department colloquium at Otterbein University (a small college), Westerville, OH, "Quantum information with atoms and light";
- September 2014, Tuesday Lunch Talk at Denison University (presentation to an audience comprised mostly of non-scientists), Granville, OH, "Quantum information with atoms and light";
- September 2014, Physics Department colloquium at Kenyon College (a small liberal arts college), Gambier, OH, "Quantum information with atoms and light";
- March 2014, Physics Department colloquium at Ohio Northern University (a small regional college), Ada, OH, "Quantum Information with Trapped Ions and Telecom Photons";
- Many other informal meetings with students, parents, and visitors about the research supported by ARO.

Honors and Awards: Nothing to Report

Protocol Activity Status:

Technology Transfer: Nothing to Report

RPPR Final Report
as of 21-Mar-2018

PARTICIPANTS:

Participant Type: PD/PI

Participant: Steven Olmschenk

Person Months Worked: 3.00

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Funding Support:

Participant Type: Undergraduate Student

Participant: Patrick Becker

Person Months Worked: 3.00

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Funding Support:

Participant Type: Undergraduate Student

Participant: Edward (Zach) Pewitt

Person Months Worked: 3.00

Project Contribution:

International Collaboration:

International Travel:

National Academy Member: N

Other Collaborators:

Funding Support:

Accomplished (Upload)

Final Report: W911NF-13-1-0410

Reporting Period: August 26, 2013 – November 25, 2017

Introduction

The objectives of this project were to measure the hyperfine energy splitting of the ground and first excited states of doubly-ionized lanthanum, and to demonstrate laser cooling and trapping of doubly-ionized lanthanum. During this grant period, we successfully completed the first goal, and made significant progress toward completing the second goal. In particular, we accomplished: optogalvanic spectroscopy of the hyperfine structure of lanthanum; ion production by laser ablation; and laser cooling and trapping of barium ions. The experiment is well-positioned to demonstrate laser cooling and trapping of doubly-ionized lanthanum in the near future.

Optogalvanic Spectroscopy

The first aim of this research was to measure the hyperfine structure of doubly-ionized lanthanum (La^{2+}), which had neither been measured nor calculated previously. Detailed information about the hyperfine structure of this ion is required for laser cooling, and may be useful for a range of experiments in astrophysics and atomic physics.

The initial focus was on saturated absorption spectroscopy in a see-through hollow-cathode lamp (HCL) with a neon fill-gas. While we measured spectra for transitions in neutral lanthanum near 654 and 658 nm, we did not detect the transition in singly-ionized lanthanum near 653 nm, nor the transitions in doubly-ionized lanthanum near 1389 and 1410 nm.

Next, we explored optogalvanic spectroscopy, which here is accomplished by using laser light to optically excite the atoms or ions in the discharge of an HCL, leading to a change in the electrical properties of the discharge and consequently altering the current through the HCL. By modulating the incident light, these tiny changes in current can be detected using lock-in techniques. Using this method, we measured the hyperfine spectrum of transitions in neutral lanthanum near 654, 796, 800, 805, and 809 nm. Analyzing these Doppler-limited spectra by accounting for the relative intensities of different hyperfine components and their frequency spacing allowed determination of the hyperfine A and B coefficients, where we found good agreement with previous measurements.

While optogalvanic spectroscopy proved to be a robust technique for observing neutral lanthanum transitions (as well as neutral barium and barium ion transitions), we were still unable to observe lanthanum ion (either singly- or doubly-ionized) transitions with this technique. After further investigation, we concluded the fill-gas in the HCL could be the reason for the absence of lanthanum ion signals, and subsequently investigated the effect on the ionic signal (in both barium and lanthanum) of different hollow cathode lamp fill-gases (neon, argon, and xenon) with an array of single-ended HCLs.

Using a lanthanum HCL with an argon fill-gas, we detected a weak optogalvanic response from the La^{2+} transition near 1410 nm. After dramatically increasing the laser power with a broadband optical amplifier, we clearly observed optogalvanic signals from the 1389 and 1410 nm transitions in La^{2+} , and determined the hyperfine A and B coefficients for these levels using analysis similar to that developed for the neutral transitions. These results were published in *Phys. Rev. A* [1], and provide essential information for future laser cooling of this ion.

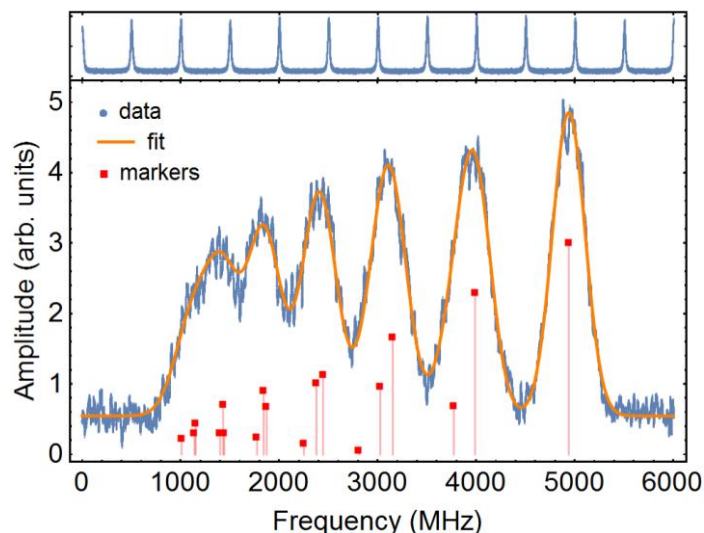


Figure 1: The hyperfine spectrum of the 1410 nm transition in doubly-ionized lanthanum. The resulting fit (orange, solid line) allowed the first determination of the hyperfine splitting of the involved levels. The resulting hyperfine transition frequencies are shown as the (red, square) markers. A comparable spectrum is observed for the 1389 nm transition [1].

Laser Ablation Production of Ions

The next effort in this research was to characterize ion production by laser ablation. Laser ablation of a solid target can be used to directly produce ions for laser cooling experiments, including multiply-charged species, and was therefore pursued as the primary method for obtaining lanthanum ions.

Ion production by laser ablation was studied using a pulsed nitrogen laser, and building a custom time-of-flight mass spectrometer to analyze the charged ablation products. Ablation with this laser proved to be efficient at producing singly-charged ions for several elements, including lanthanum. We also investigated different substrates for producing barium ions, as a pure barium source ceased yielding ions after only a small number of ablation pulses. The results of these laser ablation characterization experiments were published in *Appl. Phys. B* [2].

We also observed evidence of producing doubly-ionized lanthanum (La^{2+}) with this method, although the resolution of our time-of-flight mass spectrometer proved insufficient to unambiguously confirm this signal. Nevertheless, we also have the option to combine this technique with secondary ionization of singly-charged trapped ions by (for example) electron bombardment, and our UHV chamber has this

capability. Thus, we continue to use laser ablation as our primary method for producing ions for laser cooling and trapping.

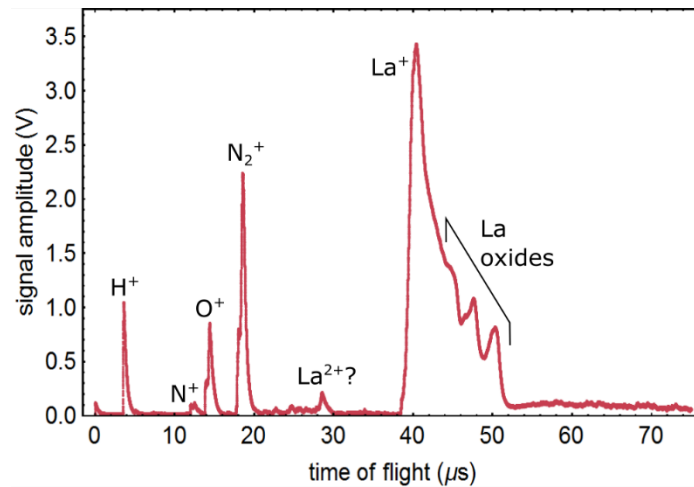


Figure 2: Time-of-flight mass spectrum of laser ablation products from a lanthanum target. A peak consistent with direct production of La²⁺ was observed, but the resolution of the mass spectrometer was insufficient to unambiguously determine this signal. Regardless, when combined with options for secondary ionization of singly-ionized lanthanum, the technique will be sufficient for producing the La²⁺ required for laser cooling.

Barium Ion Trapping and Laser Cooling

The third effort in this project was to trap and laser cool barium ions (Ba⁺). Laser cooled and trapped Ba⁺ is an invaluable diagnostic of the experiment, is also an interesting qubit candidate, may be used in future sympathetic cooling experiments, and will allow us to determine if lanthanum ions have been loaded into the trap by observing dislocations in a Ba⁺ crystal (“dark” ions not responding to the light resonant with the barium transitions).

Barium ions are produced using the laser ablation technique described above, and confined in a four-rod radiofrequency (rf) Paul trap. The ²S_{1/2} to ²P_{1/2} transition in Ba⁺ is driven by light at 494 nm, produced by a custom extended cavity diode laser (ECDL) operating near 987 nm that is frequency-doubled using a custom second-harmonic generation cavity. Population in the low-lying ²D_{3/2} level is repumped by driving the ²D_{3/2} to ²P_{1/2} transition at 650 nm with another custom ECDL. An imaging system collects fluorescence from the trapped ions, which is detected by a camera (PointGrey FL3-U3-13S2M-CS, or Nikon DS-Qi2).

We further characterized the trap loading procedure as a function of applied rf voltage and rf switching time [2]. Altogether, this verifies the operation of the trap, electronics, optical systems, laser ablation process, and vacuum chamber. With only minor modification, these systems and techniques can now be applied to lanthanum.

Next Steps: Lanthanum Ion Trapping

The final goal of this project, which is still in progress, is to trap and laser cool La^{2+} . It is expected that demonstrating laser cooling and trapping of an ion with only telecom-compatible, infrared light will have a substantial impact in both atomic physics and quantum information.

Our first method for confirming trapping of La^{2+} will be to co-trap it with laser cooled Ba^+ . Trapping additional ions will alter the observed positions of the trapped Ba^+ ions, and this deviation can be used as a basic indication of the charge/mass of the additional ions. Moreover, exciting the secular motion of the trapped ions can also be used to investigate the charge/mass of the additional ions, and confirm La^{2+} trapping.

For direct laser cooling and trapping of La^{2+} , we will use a fiber EOM with mixed rf drive to modulate the infrared laser light to produce all the necessary frequencies for depopulating the hyperfine levels in this ion. In this effort, we are aided by available electro-optical technology in the telecom regime, as the bandwidth of standard fiber EOMs encompasses the entire hyperfine manifold in both the 1389 and 1410 nm transitions. We have already tested the fiber EOMs, and are assembling the necessary rf drive components. Additionally, standard broadband optical amplifiers (as used in the hyperfine spectroscopy experiment, noted above) are readily available, and yield more than 60 mW at each wavelength.

Finally, our UHV (10^{-11} torr) chamber incorporates a high-numerical-aperture aspheric lens ($\text{NA} = 0.5$) in vacuum, enabling improved light collection for fluorescence detection of trapped La^{2+} ions. Since the wavelengths for La^{2+} are outside of the range of standard Si sensors, we have an InGaAs camera (Xenics Xeva-1.7-320 TE3) with specified quantum efficiency $>85\%$ near 1400 nm to image the ions.

In summary, all the necessary components are nearly complete, and we hope to demonstrate trapping and laser cooling of La^{2+} in the near future.

References

- [1] S. Olmschenk, P. R. Banner, J. Hankes and A. M. Nelson, "Optogalvanic spectroscopy of the hyperfine structure of the $5p^65d^2D_{3/2,5/2}$ and $5p^64f^2F_{5/2,7/2}^0$ levels of La III," *Phys. Rev. A* **96**, 032502 (2017)
- [2] S. Olmschenk and P. Becker, "Laser ablation production of Ba, Ca, Dy, Er, La, Lu, and Yb ions," *Appl. Phys. B* **123**, 99 (2017)