REPORT DOCUMENTATION PAGE	Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
04-10-2018	Final Report	1-Jul-2015 - 31-Mar-2018

4. TITLE AND SUBTITLE	
Final Report: An optimized qubit for the next generation of quantum information: The A = 133 isotope of barium	5a. CONTRACT NUMBER W911NF-15-1-0273
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHORS	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES	8. PERFORMING ORGANIZATION REPORT NUMBER
University of California - Los Angeles Office of Contract and Grant Administration 11000 Kinross Avenue, Suite 211 Los Angeles, CA 90095 -1406	

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)	10. SPONSOR/MONITOR'S ACRONYM(S) ARO
U.S. Army Research Office P.O. Box 12211 Research Triangle Park, NC 27709-2211	11. SPONSOR/MONITOR'S REPORT NUMBER(S) 67087-PH.2

12. DISTRIBUTION AVAILIBILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Wesley Campbell
UU	UU	UU	UU		19b. TELEPHONE NUMBER 626-825-1088

Standard Form 298 (Rev 8/98)
Prescribed by ANSI Std. Z39.18

RPPR Final Report
as of 09-Nov-2018

Agency Code:

Proposal Number: 67087PH

Agreement Number: W911NF-15-1-0273

INVESTIGATOR(S):

Name: Wesley Campbell
Email: wes@physics.ucla.edu
Phone Number: 6268251088
Principal: Y

Organization: **University of California - Los Angeles**
Address: Office of Contract and Grant Administration, Los Angeles, CA 900951406
Country: USA
DUNS Number: 092530369
EIN: 956006143

Report Date: 30-Jun-2018
Date Received: 04-Oct-2018
Final Report for Period Beginning 01-Jul-2015 and Ending 31-Mar-2018

Title: An optimized qubit for the next generation of quantum information: The A = 133 isotope of barium

Begin Performance Period: 01-Jul-2015
End Performance Period: 31-Mar-2018
Report Term: 0-Other

Submitted By: Wesley Campbell
Email: wes@physics.ucla.edu
Phone: (626) 825-1088

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

STEM Degrees:

STEM Participants:

Major Goals: Demonstrate the radioisotope barium-133 as an “optimized” trapped ion qubit whose unique atomic structure combines many desirable properties of different ion qubits in a single species.

Accomplishments: We trapped, laser cooled, performed the necessary spectroscopy, and operated the clock-state hyperfine qubit in 133Ba+.

Initially, state detection was done using frequency selection on the laser cooling transition. Since that time, we began to demonstrate the pieces needed to perform electron shelving for detection. In collaboration with Paul Hamilton’s group (who also need this laser), we built a 455 nm external cavity diode laser and stabilized it to the 2P3/2 <-> 2S1/2 transition in Ba+. We showed that we can use this light to pump 138Ba+ into the 2D5/2 shelving state, which is followed by a ~30 s recovery via the finite lifetime of that state. Naturally, we would like to “de-shelve” the ions more quickly than this, which requires light at 614 nm, which is challenging. We purchased and characterized a series of LEDs that have some overlap with 614 nm, and prepared to test this as a deshelving method.

We also started working toward driving hyperfine transitions in the 2D3/2 state of 133Ba+ with applied RF (just less than 1 GHz). We began by trying to couple the RF directly to one of the trap rods with the goal of achieving a Rabi frequency on the order of 1 MHz

We also published our first spectroscopy results on this species in PRL. The APS decided to feature this paper with a synopsis in Physics.

Training Opportunities: Both the graduate student (Justin Christensen) and the postdoc (Dave Hucul) on this project attended conferences (typically, DAMOP) during this project and presented their results.

Results Dissemination: Our work was published in PRL, and a few pieces for the media were made, including a Synopsis in Physics.

Honors and Awards: WCC was selected by the Editorial Board of J. Phys. B. as an "Emerging Leader," 2017

Graduate student Justin Christensen won Best Poster prize at the North American Conference for Trapped Ions in Boulder, CO.

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: David Hucul
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

Participant Type: Graduate Student (research assistant)
Participant: Justin Christensen
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
International Collaboration:
International Travel:
National Academy Member: N
Other Collaborators:

ARTICLES:

Publication Type: Journal Article Peer Reviewed: Y **Publication Status:** 1-Published
Journal: Physical Review Letters
Publication Identifier Type: DOI Publication Identifier: 10.1103/PhysRevLett.119.100501
Volume: 119 Issue: 10 First Page #: 100501
Date Submitted: 10/4/18 12:00AM Date Published: 9/6/17 7:00AM
Publication Location:
Article Title: Spectroscopy of a Synthetic Trapped Ion Qubit
Authors: David Hucul, Justin E. Christensen, Eric R. Hudson, Wesley C. Campbell
Keywords: Research Areas Quantum information with trapped ions Physical Systems Trapped ions Techniques Spectroscopy Atomic, Molecular & OpticalQuantum Information
Abstract: 133Ba+ has been identified as an attractive ion for quantum information processing due to the unique combination of its spin-1/2 nucleus and visible wavelength electronic transitions. Using a microgram source of radioactive material, we trap and laser cool the synthetic A=133 radioisotope of barium II in a radio-frequency ion trap. Using the same, single trapped atom, we measure the isotope shifts and hyperfine structure of the 6 2P1/2? 6 2S1/2 and 6 2P1/2?5 2D3/2 electronic transitions that are needed for laser cooling, state preparation, and state detection of the clock-state hyperfine and optical qubits. We also report the 6 2P1/2?5 2D3/2 electronic transition isotope shift for the rare A=130 and 132 barium nuclides, completing the spectroscopic characterization necessary for laser cooling all long-lived barium II isotopes.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

RPPR Final Report
as of 09-Nov-2018

Contract No: (e.g., W911NF-15-1-0273)

Project Title: An optimized qubit for the next generation of quantum information: The A = 133 isotope of barium

Principal Investigator: Wes Campbell, UCLA

Co- Investigators: Eric Hudson, UCLA

Postdoctoral Associates: David Hucul, UCLA

Graduate Students: Justin Christensen, UCLA

Start Date: 07/01/2015
End Date: 06/30/2017

Main Project Goals:
Demonstrate the radioisotope barium-133 as an "optimized" trapped ion qubit whose unique atomic structure combines many desirable properties of different ion qubits in a single species.

Project Description:
Among the atomic ions that could be used for quantum information storage and processing, barium-133, a man-made radioisotope, possesses several unique and desirable properties that are not found in any naturally occurring species. These properties combine to make it a nearly ideal qubit. Specifically, the barium electronic structure provides transitions in the visible part of the electromagnetic spectrum, enabling the use of the high-power lasers, low-loss fibers, high quantum efficiency detectors, and other optical equipment not available to ion species currently in use. The nuclear structure of barium-133 provides a robust hyperfine clock state qubit that is easy to initialize and detect, yet protects the qubit coherence during shuttling and storage. These features make it compatible with existing traps and in many ways superior to species currently in use, particularly for a QCCD architecture and for remote linking via photons. Under this program, we have developed techniques to load and cool $^{133}Ba^{+}$, as well as perform state initialization and state detection. We have also shown that the radioactivity of this isotope is a complication that can be dealt with in a way that is compatible with essentially all existing trapped ion quantum information processors, and is justified by the advantages of this species over the other ions in use.

Accomplishments since July QCPR meeting:
We trapped, laser cooled, performed the necessary spectroscopy, and operated the clock-state hyperfine qubit in $^{133}Ba^{+}$.

Initially, state detection was done using frequency selection on the laser cooling transition. Since that time, we began to demonstrate the pieces needed to perform electron shelving for detection. In collaboration with Paul Hamilton's group (who also need this laser), we built a

455 nm external cavity diode laser and stabilized it to the $^2P_{3/2}$ <-> $^2S_{1/2}$ transition in Ba^+. We showed that we can use this light to pump $^{138}Ba^+$ into the $^2D_{5/2}$ shelving state, which is followed by a ~30 s recovery via the finite lifetime of that state. Naturally, we would like to "de-shelve" the ions more quickly than this, which requires light at 614 nm, which is challenging. We purchased and characterized a series of LEDs that have some overlap with 614 nm, and prepared to test this as a deshelving method.

We also started working toward driving hyperfine transitions in the $^2D_{3/2}$ state of $^{133}Ba^+$ with applied RF (just less than 1 GHz). We began by trying to couple the RF directly to one of the trap rods with the goal of achieving a Rabi frequency on the order of 1 MHz

We also published our first spectroscopy results on this species in PRL. The APS decided to feature this paper with a synopsis in Physics.

Milestone summary

Completed	**Future**
Obtain ^{133}Ba	D Microwave transitions
Trap $^{133}Ba^+$	Better state prep, detection
S,P,D state spectroscopy	
Laser cooling $^{133}Ba^+$	
HF qubit state preparation	
HF qubit state detection	
S microwave transitions	
Single qubit operations	

Publications/Patents:

- David Hucul, Justin E. Christensen, Eric R. Hudson, and Wesley C. Campbell. Spectroscopy of a Synthetic Trapped Ion Qubit. *Phys. Rev. Lett.* **119**, 100501 (2017)

Presentations:

- D. Hucul, *et al.* "Laser-cooling and trapping the Goldilocks Qubit: $^{133}Ba^+$" 1st North American Conference on Trapped Ions, Boulder Co, August 2017

Additional Information:

Relevant data/figures