COHERENT SPECTROSCOPY OF ULTRA-COLD MERCURY FOR THE UV TO VUV

R Jason Jones
ARIZONA UNIV BOARD OF REGENTS TUCSON

11/20/2015
Final Report

DISTRIBUTION A: Distribution approved for public release.
**COHERENT SPECTROSCOPY OF ULTRA-COLD MERCURY FOR THE UV TO VUV**

**Jones, R. Jason**

**University of Arizona**
1630 E University Blvd
Tucson, AZ 85721

**AFOSR**
875 N. Randolph St. Room 3112
Arlington VA 22203

**Narrow UV transitions in atomic Hg can be utilized for a high quality atomic frequency standard. The primary goal of the research supported by this grant was the development of a laser-cooled source of ultracold Hg atoms and the spectroscopic study of the doubly-forbidden "clock" transition to better understand its potential as a future atomic clock. During this funding period a novel UV laser system was developed to efficiently cool and trap atomic Hg to temperatures below 100 microKelvin. The narrow \(^1S_0\) to \(^3P_0\) clock transition was measured and used to determine the temperature of the Hg ensemble. The grant supported the PhD research of two students.**

**DISTRIBUTION A:** Distribution approved for public release
### Instructions for Completing SF 298

1. **Report Date.** Full publication date, including day, month, if available. Must cite at least the year and be Year 2000 compliant, e.g. 30-06-1998; xx-06-1998; xx-xx-1998.

2. **Report Type.** State the type of report, such as final, technical, interim, memorandum, master’s thesis, progress, quarterly, research, special, group study, etc.

3. **Dates Covered.** Indicate the time during which the work was performed and the report was written, e.g., Jun 1997 - Jun 1998; 1-10 Jun 1996; May - Nov 1998; Nov 1998.

4. **Title.** Enter title and subtitle with volume number and part number, if applicable. On classified documents, enter the title classification in parentheses.

5a. **Contract Number.** Enter all contract numbers as they appear in the report, e.g. F33615-86-C-5169.

5b. **Grant Number.** Enter all grant numbers as they appear in the report, e.g. AFOSR-82-1234.

5c. **Program Element Number.** Enter all program element numbers as they appear in the report, e.g. 61101A.

5d. **Project Number.** Enter all project numbers as they appear in the report, e.g. 1F665702D1257; ILIR.

5e. **Task Number.** Enter all task numbers as they appear in the report, e.g. 05; RF0330201; T4112.

5f. **Work Unit Number.** Enter all work unit numbers as they appear in the report, e.g. 001; AFAPL30480105.

6. **Author(s).** Enter name(s) of person(s) responsible for writing the report, performing the research, or credited with the content of the report. The form of entry is the last name, first name, middle initial, and additional qualifiers separated by commas, e.g. Smith, Richard, J, Jr.

7. **Performing Organization Name(s) and Address(es).** Self-explanatory.

8. **Performing Organization Report Number.** Enter all unique alphanumeric report numbers assigned by the performing organization, e.g. BRL-1234; AFWL-TR-85-4017-Vol-21-PT-2.

9. **Sponsoring/Monitoring Agency Name(s) and Address(es).** Enter the name and address of the organization(s) financially responsible for and monitoring the work.

10. **Sponsoring/Monitor’s Acronym(s).** Enter, if available, e.g. BRL, ARDEC, NADC.

11. **Sponsoring/Monitor’s Report Number(s).** Enter report number as assigned by the sponsoring/monitoring agency, if available, e.g. BRL-TR-829; -215.

12. **Distribution/Availability Statement.** Use agency-mandated availability statements to indicate the public availability or distribution limitations of the report. If additional limitations/restrictions or special markings are indicated, follow agency authorization procedures, e.g. RD/FRD, PROPIN, ITAR, etc. Include copyright information.

13. **Supplementary Notes.** Enter information not included elsewhere such as: prepared in cooperation with; translation of; report supersedes; old edition number, etc.

14. **Abstract.** A brief (approximately 200 words) factual summary of the most significant information.

15. **Subject Terms.** Key words or phrases identifying major concepts in the report.

16. **Security Classification.** Enter security classification in accordance with security classification regulations, e.g. U, C, S, etc. If this form contains classified information, stamp classification level on the top and bottom of this page.

17. **Limitation of Abstract.** This block must be completed to assign a distribution limitation to the abstract. Enter UU (Unclassified Unlimited) or SAR (Same as Report). An entry in this block is necessary if the abstract is to be limited.
The primary goal of the research supported by this grant was the development of a laser-cooled source of ultra-cold Hg atoms and the spectroscopic study of the doubly-forbidden "clock" transition to better understand its potential as a future atomic clock. During this funding period a novel UV laser system was developed to efficiently cool and trap atomic Hg to temperatures below 100 microKelvin. This work demonstrated that, unlike other alkaline earth-like systems that require 2-stages a laser cooling (e.g. Sr and Yb), a single-stage of laser cooling can be used to capture over $10^6$ atoms and reduce their temperature to a range where it is feasible to directly load them into an optical lattice. The narrow $^1S_0 \rightarrow ^3P_0$ clock transition was measured during this work and was used to determine the temperature of the Hg ensemble. The grant supported the PhD research of two students.

Two novel laser systems have been developed for this project. The primary challenge was in the development of the source at 254nm for laser cooling and trapping on the $^1S_0$ to $^3P_1$ transition. We designed and constructed a system based on optically-pumped semiconductor laser technology (OPSL). Details of this system can be found in [1]. The home-built OPSL provides >1 Watt of single frequency, narrow line radiation at 1016nm. This is frequency quadrupled with high efficiency using two successive cavity enhanced frequency doubling stages (LBO and BBO) to generate over 100mW of UV light at 254 nm.

This OPSL based system is used to reliably generate the Hg MOT (see Fig. 1). Characterization of the MOT temperature and atom number was completed, using standard computer automated imaging and time-of-flight techniques. Both fermionic and bosonic isotopes of Hg have been characterized. We were able to demonstrate temperatures at the ~100 microKelvin level.

We have measured the narrow "clock" transition of Hg using a fiber based cw laser source. The spectroscopy laser system utilizes a cw fiber laser that is amplified and frequency doubled in a single pass using periodically-poled lithium niobate (PPLN). This provides a reliable, nearly turn-key source of green light. A resonant doubling cavity is then used to generate >10mW of light at the clock transition of ~265nm. In order to resolve the narrow $^1S_0$ to $^3P_0$ transition, the laser system must be stable and tunable on the timescale of several seconds. To accomplish this, we first lock a secondary external cavity semiconductor diode laser to an ultrastable ULE reference cavity (which is vibrationally and thermally isolated inside a vacuum chamber- see
Fig 2). An optical phase-lock loop is then used to stabilize the fiber-based system to the diode laser. This enables linewidth narrowing of the fiber laser system to 100’s Hz levels while simultaneously allowing for a broad and controlled tuning range. In this way we are able to slowly scan the UV laser system to locate the clock transition (using the standard technique of MOT depletion).

As a secondary frequency reference for the lab, we have built a saturated absorption iodine system. This was needed in order to initially locate the Hg clock transition. Iodine reference lines near the green laser wavelength of 531nm (1016nm/2) are fortuitously located within ~2GHz of the Hg transition (after the final doubling stage 531nm -> 265.5nm). Using these transitions as reference, we calibrated the frequency of the ultra-stable reference cavity and slowly tuned to the clock transition frequency. In order to measure the clock transition in the absence of Stark shifts from the cooling laser light, we strobe the MOT beams and probe beams on and off at different time intervals using AOM’s. The measured clock transition is shown in Fig. 3. The measured Doppler-broadened linewidth was consistent with the temperature estimates from time-of-flight measurements.
Figure 2. (a) The UHF cavity made of ULE glass is placed (b) inside a vacuum chamber to provide environmental isolation. (c), (d) An additional heat shield within the chamber provides further isolation between the UHF cavity and thermal radiation from the chamber walls.

Figure 3. Spectroscopy of the Hg$^{199}$ clock transition in the absence of the MOT beams.
Publications


http://dx.doi.org/10.1117/12.2004351

1.

1. Report Type
Final Report

Primary Contact E-mail
Contact email if there is a problem with the report.
rjjones@optics.arizona.edu

Primary Contact Phone Number
Contact phone number if there is a problem with the report
520-235-6051

Organization / Institution name
University of Arizona

Grant/Contract Title
The full title of the funded effort.
Coherent Spectroscopy of Ultra-cold Hg from the UV to VUV

Grant/Contract Number
AFOSR assigned control number. It must begin with "FA9550" or "F49620" or "FA2386".
FA9550-09-1-0563

Principal Investigator Name
The full name of the principal investigator on the grant or contract.
R. Jason Jones

Program Manager
The AFOSR Program Manager currently assigned to the award
Tatjana Curcic

Reporting Period Start Date
07/15/2009

Reporting Period End Date
08/28/2015

Abstract
The primary goal of the research supported by this grant was the development of a laser-cooled source of ultra-cold Hg atoms and the spectroscopic study of the doubly-forbidden \"clock\" transition to better understand its potential as a future atomic clock. During this funding period a novel UV laser system was developed to efficiently cool and trap atomic Hg to temperatures below 100 microKelvin. This work demonstrated that, unlike other alkaline earth-like systems that require 2-stages a laser cooling (e.g. Sr and Yb), a single-stage of laser cooling can be used to capture over 106 atoms and reduce their temperature to a range where it is feasible to directly load them into an optical lattice. The narrow $1S_0 \rightarrow 3P_0$ clock transition was measured during this work and was used to determine the temperature of the Hg ensemble. The grant supported the PhD research of two students.

Two novel laser systems have been developed for this project. The primary challenge was in the development of the source at 254nm for laser cooling and trapping on the $1S_0 \rightarrow 3P_1$ transition. We designed and constructed a system based on optically-pumped semiconductor laser technology (OPSL). The home-built OPSL provides >1 Watt of single frequency, narrow line radiation at 1016nm. This is frequency quadrupled with high efficiency using two successive cavity enhanced frequency doubling stages (LBO and BBO) to generate over 100mW of UV light at 254 nm.
We have measured the narrow “clock” transition of Hg using a fiber based cw laser source that is stabilized to an reference cavity for short term stability. The fiber laser is amplified and frequency doubled in a single pass using periodically-poled lithium niobate (PPLN). This provides a reliable, nearly turn-key source of green light. A resonant doubling cavity is then used to generate >10mW of light at the clock transition of ~265nm. In order to measure the clock transition in the absence of Stark shifts from the cooling laser light, we strobe the MOT beams and probe beams on and off at different time intervals using AOM’s. The measured Doppler-broadened linewidth was consistent with the temperature estimates from time-of-flight measurements.

Distribution Statement
This is block 12 on the SF298 form.

Explanation for Distribution Statement
If this is not approved for public release, please provide a short explanation. E.g., contains proprietary information.

SF298 Form
Please attach your SF298 form. A blank SF298 can be found here. Please do not password protect or secure the PDF
The maximum file size for an SF298 is 50MB.

SF298_Jones_Hg_AFOSR.pdf

Upload the Report Document. File must be a PDF. Please do not password protect or secure the PDF. The maximum file size for the Report Document is 50MB.

RJJones_AFOSR_Final Report_Hg.pdf

Upload a Report Document, if any. The maximum file size for the Report Document is 50MB.

Archival Publications (published) during reporting period:

Justin R. Paul ; Christian R. Lytle ; Yushi Kaneda ; Jerome Moloney ; Tsuei-Lian Wang, R. J. Jones, "Optically pumped external-cavity semiconductor lasers for precision spectroscopy and laser cooling of atomic Hg ", Proc. SPIE 8606, Vertical External Cavity Surface Emitting Lasers (VECSELs) III, 86060R (February 18, 2013); doi:10.1117/12.2004351; http://dx.doi.org/10.1117/12.2004351

Changes in research objectives (if any):

Changes in AFOSR Program Manager, if any:

Extensions granted or milestones slipped, if any:
A 1 year extension was granted in 2013, and a no-cost extension was granted in 2014.

AFOSR LRIR Number

LRIR Title

Reporting Period

Laboratory Task Manager

Program Officer

Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, $K)

DISTRIBUTION A: Distribution approved for public release
<table>
<thead>
<tr>
<th></th>
<th>Starting FY</th>
<th>FY+1</th>
<th>FY+2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salary</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equipment/Facilities</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supplies</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Report Document
Report Document - Text Analysis
Report Document - Text Analysis
Appendix Documents

2. Thank You

E-mail user

Nov 06, 2015 02:21:47 Success: Email Sent to: rjones@optics.arizona.edu