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RPPR Final Report
as of 14-Dec-2022

Agency Code: 21XD

Proposal Number: 64897PEQC **Agreement Number: W911NF-15-1-0261**

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Report Date: 31-Mar-2019 Date Received: 13-Dec-2022
Final Report for Period Beginning 01-Jun-2015 and Ending 31-Dec-2018
Title: Improved Qubit Measurement through Background-free Detection of Trapped Ion Fluorescence
Begin Performance Period: 01-Jun-2015 **End Performance Period:** 31-Dec-2018
Report Term: 0-Other
Submitted By: Wesley Campbell Email: wes@physics.ucla.edu
Phone: (310) 825-1088
Distribution Statement: 1-Approved for public release; distribution is unlimited.

STEM Degrees: 3 **STEM Participants:** 6

Major Goals: 1. Develop the use of picosecond mode-locked laser pulses for background-free projective measurements of individual 171Yb+ spins in a trapped ion quantum processor.
2.Reject background scatter through fast gating of the fluorescence collection.
3.Use this to improve the speed and accuracy of the readout.

Accomplishments: We successfully obtained and integrated a frequency-doubled, piscosecond mode-locked (ML)laser into our trapped Yb+ system. The pulses were characterized with a home-built autocorrelator and a precision optical delay was built to produce 369.5 nm pulse pairs with interferometrically-defined intra-pair delays. Laser-induced fluorescence (LIF) was obtained from a trapped ion excited by the ML pulses (with a cw 935 nm repump laser also illuminating the ion).

We developed electron shelving of Yb+ hyperfine qubits, which was not thought to be possible (and has now been adopted by multiple groups), essentially as a stepping stone to this work.

For state detection of optical (or shelved-hyperfine) qubits, the ML pulse bandwidth was much smaller than the qubit splitting, and temporal background rejection allowed us to achieve a single-shot detection fidelity of 0.9993(+3 -6).

For direct state detection of (un-shelved) hyperfine qubits, we brought together techniques from quantum information science and coherent control, developing Ramsey spectroscopy to gain a sub-femtosecond view of the complex motion of the valence electron orbiting the single atom between excitation pulses (with a table-top system). This unique, time-domain picture of the inner workings of a quantum bit allowed us to discern and control the microscopic dynamics of the atom's electron to demonstrate direct detection of the hyperfine qubit state by suppressing unwanted excitations through destructive interference of electron wavepackets.

Other techniques developed here include the use of Ramsey delay to perform hyperfine spectroscopy of a single atom, the use of Loomis-Wood diagrams for time-domain analysis (a sort of Polya orchard problem), and the observation of atomic wavepacket dynamics with sub-femtosecond resolution with a table-top system.

Along the way, we also made some unexpected discoveries.

Chief among these was the observation of phonon lasing when a trapped ion is illuminated by a mode-locked laser. This took us a while to figure out, but the quantitative description of this phenomenon matched the data well and showed why ions aren't boiled out of the trap by blue-detuned comb teeth (and important observation for planned deep ultraviolet spectroscopy of exotic species like He+ with ML lasers). We derived the Doppler limit for cooling with combs for the first time, and used this to explain a puzzling result from 2006 in which Cd+ was cooled to lower temperatures than the authors of that work thought possible.

We also (WCC and Paul Hamilton) developed a novel scheme to use a single ion as a matter-wave Sagnac gyroscope and published this as a proposal. This project was later funded by ONR, and there is now a group in Japan that is about to demonstrate this gyroscope for the first time.

Training Opportunities: Three students (Michael Ip, Anthony Ransford, and Conrad Roman) graduated with PhDs that included significant work under this grant. One postdoc (Andrew Jayich) learned enough ion trapping that he started his own group on the topic and is now a tenured associate professor at UCSB. All graduate and postdoctoral personnel went to multiple conferences to present this work, typically at least 1 per year.

Results Dissemination: The progress and results of this program were disseminated to the scientific community in the usual way (peer-reviewed publications, talks at conferences, seminars, and colloquia, etc.)

The matter-wave Sagnac gyroscope proposal found a wider audience than is typical, and was featured in Physics World and IOP news and a special issue of the Journal of Physics B. This special issue was by invitation and called "Emerging leaders"

Honors and Awards: The Journal of Physics B invited me to submit a paper to their "Emerging Leaders" issue, which is where the matter-wave Sagnac gyroscope idea that was from this program appeared.

Protocol Activity Status:

Technology Transfer: Nothing to Report

PARTICIPANTS:

Participant Type: PD/PI
Participant: Wes Campbell
Person Months Worked: 5.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Michael Ip
Person Months Worked: 10.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Anthony Ransford
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:
National Academy Member: N

Participant Type: Graduate Student (research assistant)
Participant: Conrad Roman
Person Months Worked: 12.00 **Funding Support:**
Project Contribution:

National Academy Member: N

Participant Type: Postdoctoral (scholar, fellow or other postdoctoral position)
Participant: Andrew Jayich
Person Months Worked: 6.00 **Funding Support:**
Project Contribution:
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Participant Type: Graduate Student (research assistant)
Participant: Xueping Long
Person Months Worked: 2.00 **Funding Support:**
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Article Title: Phonon Lasing from Optical Frequency Comb Illumination of Trapped Ions
Authors: Michael Ip, Anthony Ransford, Andrew M. Jayich, Xueping Long, Conrad Roman, Wesley C. Campbell
Keywords: Research Areas Acoustic phononsAtom & ion coolingCooling & trappingFrequency combs & self-phase locking Condensed Matter & Materials PhysicsAtomic, Molecular & Optical
Abstract: We demonstrate the use of a frequency-doubled optical frequency comb to load, cool, and crystallize trapped atomic ions as an alternative to ultraviolet (UV) or even deep UV continuous-wave lasers. We find that the Doppler shift from the atom’s oscillation in the trap, driven by the blue-detuned comb teeth, introduces additional cooling and amplification which gives rise to steady-state phonon lasing of the ion’s harmonic motion in the trap. The phonon laser’s gain saturation keeps the optical frequency comb from continually adding energy without bound. This protection allows us to demonstrate loading and crystallization of hot ions directly with the comb, eliminating the need for a continuous-wave cooling laser, a technique that is extendable to the deep UV.
Distribution Statement: 3-Distribution authorized to U.S. Government Agencies and their contractors
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Article Title: Rotation sensing with trapped ions
Authors: W C Campbell, P Hamilton
Keywords: atom interferometry, Sagnac, quantum metrology, gyroscope, trapped ion
Abstract: We present a protocol for rotation measurement via matter-wave Sagnac interferometry using trapped ions. The ion trap based interferometer encloses a large area in a compact apparatus through repeated round-trips in a Sagnac geometry. We show how a uniform magnetic field can be used to close the interferometer over a large dynamic range in rotation speed and measurement bandwidth without contrast loss. Since this technique does not require the ions to be confined in the Lamb–Dicke regime, Doppler laser cooling should be sufficient to reach a sensitivity of ${ \mathcal S }=1.4\times {10}^{-6}\,{\rm{rad}}\,{{\rm{s}}}^{-1}\,{{\rm{H}}{\rm{z}}}^{-1/2}$.
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Volume: 22 Issue: 7 First Page #: 073038
Date Submitted: 12/13/22 12:00AM Date Published: 7/1/20 7:00AM
Publication Location:
Article Title: Coherent control for qubit state readout
Authors: Conrad Roman, Anthony Ransford, Michael Ip, Wesley C Campbell
Keywords: coherent control, quantum information, trapped ions
Abstract: We present a protocol for rotation measurement via matter-wave Sagnac interferometry using trapped ions. The ion trap based interferometer encloses a large area in a compact apparatus through repeated round-trips in a Sagnac geometry. We show how a uniform magnetic field can be used to close the interferometer over a large dynamic range in rotation speed and measurement bandwidth without contrast loss. Since this technique does not require the ions to be confined in the Lamb–Dicke regime, Doppler laser cooling should be sufficient to reach a sensitivity of ${ \mathcal S }=1.4\times {10}^{-6}\,{\rm{rad}}\,{{\rm{s}}}^{-1}\,{{\rm{H}}{\rm{z}}}^{-1/2}$.
Distribution Statement: 1-Approved for public release; distribution is unlimited.
Acknowledged Federal Support: **Y**

DISSERTATIONS:

Publication Type: Thesis or Dissertation
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Date Received: 04-Oct-2018 Completion Date: 5/1/18 11:33PM
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Authors: Michael Ip
Acknowledged Federal Support: **N**

Publication Type: Thesis or Dissertation
Institution: UCLA Physics & Astronomy Dept.
Date Received: 13-Dec-2022 Completion Date: 6/1/21 11:29PM
Title: Expanding the 171Yb+ toolbox: the 2F7/2 state as a resource for quantum information science
Authors: Conrad Roman
Acknowledged Federal Support: **N**

RPPR Final Report
as of 14-Dec-2022

Publication Type: Thesis or Dissertation
Institution: UCLA Physics & Astronomy Dept.
Date Received: 13-Dec-2022 Completion Date: 6/1/20 7:00AM
Title: Old Dog, New Trick: High Fidelity, Background-free State Detection of an Ytterbium Ion Qubit
Authors: Anthony Ransford
Acknowledged Federal Support: **N**

Partners

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I certify that the information in the report is complete and accurate:
Signature: Wesley Campbell
Signature Date: 12/13/22 4:56PM

Abstract:

One of the crucial criteria for a quantum information processor (be it a quantum computer or a quantum simulator) is that at the end of the process, the user must be able to faithfully read out the result. This result is typically encoded in one or more projective measurements of each spin on a measurement basis. We developed the use of picosecond mode-locked laser pulses for background-free projective measurements of individual ^{171}Yb$^+$ spins in a trapped ion quantum processor and used this to improve the accuracy of the readout. By limiting the pulse sequence to a few hundred picoseconds, photon detection events during this time can be ignored as likely background scatter, while detection events outside this window will have therefore faithfully indicated the result of the projective measurement. This technology would enable researchers to abandon the imaging system entirely, allowing large solid-angle collection by essentially putting detector photocathodes right next to the ions. The reduction in detection errors this should bring will allow accurate readout of larger quantum simulations than are currently possible.

Detailed Objectives:

1. Trap Yb$^+$ in Translume trap
2. Couple mode-locked (ML) laser light onto ion from side ports
3. Non-destructive illumination of ion with ML light
4. Frequency-selective excitation in comb regime
5. Frequency-selective excitation with delay stage (a.k.a. Ramsey spectroscopy)
6. Load, cool, state prep, detect ^{171}Yb$^+$ hyperfine qubit
7. State-selective excitation with broadband pulses
8. Time-tagged fluorescence to reject background scatter

Findings:

1. **Trap Yb$^+$ in Translume trap**
   We diagnosed a broken *in vacuo* connection and vented, fixed, and pumped out the system again, which allowed us to trap single ions in this trap for the first time.
2. **Couple ML laser light onto ion from side ports**
   The side ports of our trap are tunnels through the trap substrate that exit the radio-frequency (RF) ring radially. The quality of focus required to get high-power UV light cleanly through these ports was challenging, but we were able to do this without causing noticeable charging of the trap electrodes.

   It was from thinking about the momentum kicks that the ion experiences during illumination by ML pulses that we (WCC and colleague Paul Hamilton) realized that this could be used to make an atom interferometer. We developed a novel scheme to use a single ion as a matter-wave Sagnac gyroscope and published this as a proposal. This project was later funded by ONR, and there is now a group in Japan that is about to demonstrate this gyroscope for the first time. This was published in the "Emerging Leaders" issue of J. Phys. B. [1].

3. **Non-destructive illumination of ion with ML light**
   There was some fear that when we would shine a near-resonant comb on the ion, the blue-detuned teeth would boil it out of the trap. Our first illuminations of the ion with resonant 369.5 nm ML light caused the shape of the ion to smear out on the screen, but maintain a fixed shape. We later discovered that this was phonon lasing, and this led to a whole paper on the topic in PRL [2]. Our model showed why ions aren't boiled out of the trap by blue-detuned comb teeth (and important observation for planned deep ultraviolet spectroscopy of exotic species like He+ with ML lasers). We derived the Doppler limit for cooling with combs for the first time, and used this to explain a puzzling result from 2006 in which Cd+ was cooled to lower temperatures than the authors of that work thought possible.
4. **Frequency-selective excitation in comb regime**
   The "comb regime" here refers to the situation where the radiative lifetime of the excited state is long enough that excitations survive to see multiple pulses from the laser. The contrast would be the "pulse regime," where complete decay between pulses means that the ion sees the single-pulse spectrum, as opposed to the frequency comb. As described above, this unexpectedly led to the discovery of phonon lasing in the trap, but we also developed the theory governing the transition between the two regimes, which highlighted the surprisingly high tooth contrast that can persist even when the inter-pulse period is well longer than the excited state lifetime.
5. **Frequency-selective excitation with delay stage (a.k.a. Ramsey spectroscopy)**
   The delay stage we constructed is a Mach-Zehnder interferometer with a path length difference exceeding the pulse length. We used a cw laser to reference the delay at an interferometric level. Spectroscopy done as a function of the delay time between pulses is a type of Ramsey sequence, and we were able to record Ramsey fringes on the strong optical transition.

   Next, we brought together techniques from quantum information science and coherent control, using Ramsey spectroscopy to gain a sub-femtosecond view of the complex motion of the valence electron orbiting the single atom between excitation pulses (with a table-top system). Unravelling the dynamics from the $^{171}Yb^{+}$ Ramsey fringes required the development or adaptation of a few techniques, including the use of Loomis-Wood diagrams for time-domain analysis (a Polya orchard-visibility problem), and the observation of atomic wavepacket dynamics with sub-femtosecond resolution with a table-top system, which was published in NJP [3]. This unique, time-domain picture of the inner workings of a quantum bit allowed us to discern and control the microscopic dynamics of the atom's electron.

6. **Load, cool, state prep, detect $^{171}Yb^+$ hyperfine qubit**
   This step came pretty soon after our first successful trapping in the Translume trap, and involved essentially well-known techniques from quantum information processing with this species. The new feature we implemented here was the first demonstration of electron shelving detection in $^{171}Yb^+$, a technique that most of us thought was not available in this species. This was later developed into a record-setting method as part of other ARO supported work (and one that has now been adopted by other groups), but the first demonstration was from this work and appeared in Ref. [3]
7. **State-selective excitation with broadband pulses**
   Using the Ramsey setup, we found the delay stage setting at which the desired transition could be driven while the undesired transitions were suppressed through destructive interference of electron wavepackets. This allowed us to excite the ion in a qubit-state-dependent manner with mode-locked pulses much more broad in frequency than the qubit splitting [3].
8. **Time-tagged fluorescence to reject background scatter**
   We first demonstrated temporal background scatter rejection using electron-shelved detection, achieving a single-shot readout fidelity of 0.9993 (+3 -6) [3]. For this, we had to use special electronics to allow sub-ns time-tagging of the photon arrival times, but it worked well enough for us to achieve very high fidelity in a regime where most photon counts were actually background scatter.

   For direct state detection of an unshelved hyperfine qubit, we used the state-selective excitation described above and were able to see Rabi flopping of the qubit, but not at a level where the fidelity would be competitive with continuous-wave laser techniques [3].

Publications:

[1] "Rotation sensing with trapped ions," W. C. Campbell and P. Hamilton. *J. Phys. B: At. Mol. Opt. Phys.* **50**, 064002 (2017)

[2] "Phonon lasing from optical frequency comb illumination of trapped ions," Michael Ip, Anthony Ransford, Andrew M. Jayich, Xueping Long, Conrad Roman, and Wesley C. Campbell. *Phys. Rev. Lett.* **121**, 043201 (2018)

[3] "Coherent control for qubit state readout," Conrad Roman, Anthony Ransford, Michael Ip, and Wesley C. Campbell. *New J. Phys.* **22**, 073038 (2020)