AFRL-AFOSR-VA-TR-2021-0012

Programmable 2D Arrays of Interacting Quantum Spins Using Trapped Ions

Philip Richerme
TRUSTEES OF INDIANA UNIVERSITY
230 W 41ST STREET FL 7
NEW YORK, NY, 47405-1106
US

02/01/2021
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

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
01-02-2021

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*
15 Jun 2016 - 14 Jun 2020

4. TITLE AND SUBTITLE
Programmable 2D Arrays of Interacting Quantum Spins Using Trapped Ions

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA9550-16-1-0277

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Philip Richerme

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
TRUSTEES OF INDIANA UNIVERSITY
230 W 41ST STREET FL 7
NEW YORK, NY 47405-1106
US

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AF 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-2021-0012

12. DISTRIBUTION/AVAILABILITY STATEMENT
A Distribution Unlimited: PB Public Release

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This document summarizes the advances in research performed under AFOSR YIP award FA9550-16-1-0277. The scope of this work spanned both theory and experimental developments. On the theory side, three publications proposed (1) new approaches to quantum simulation in two dimensional ion arrays, (2) a new method to achieve string-order in ion systems by periodically driving the interactions, and (3) the first proposal for realizing full Heisenberg interactions in an ion lattice. Experimentally, this work started from a vacant laboratory, and built up a full suite of laser systems, ion traps, and vacuum chambers. In the final year of this project, these efforts culminated in the trapping of Yb+ within a two-dimensional array as well as quantum manipulation of these ion configurations.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			GRACE METCALFE
U	U	U	UU	6	19b. TELEPHONE NUMBER *(Include area code)* (703) 696-9740

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

Programmable 2D Arrays of Interacting Quantum Spins Using Trapped Ions

Final Project Report

Philip Richerme

Physics Department, Indiana University, Bloomington IN 47405, USA

Executive Summary

This document summarizes the advances in research performed under AFOSR YIP award FA9550-16-1-0277. The scope of this work spanned both theory and experimental developments. On the theory side, three publications proposed (1) new approaches to quantum simulation in two-dimensional ion arrays, (2) a new method to achieve string-order in ion systems by periodically driving the interactions, and (3) the first proposal for realizing full Heisenberg interactions in an ion lattice. Experimentally, this work started from a vacant laboratory, and built up a full suite of laser systems, ion traps, and vacuum chambers. In the final year of this project, these efforts culminated in the trapping of Yb+ within a two-dimensional array as well as quantum manipulation of these ion configurations.

Publications

"Two-dimensional ion crystals in radio-frequency traps for quantum simulation."
P. Richerme, *Phys. Rev. A* **94**, 032320 (2016).

"String order via Floquet interactions in atomic systems."
T.E. Lee, Y.N. Joglekar, and P. Richerme, *Phys. Rev. A* **94**, 023610 (2016).

"Long-range Heisenberg models in quasi-periodically driven crystals of trapped ions.
A. Bermudez, L. Tagliacozzo, G. Sierra, and P. Richerme, *Phys. Rev. B.* **95**, 024431 (2017).

Theory Investigations

During the initial construction of the experimental apparatus, I have authored/co-authored three publications that propose new approaches to quantum simulation, and new experiments that can be performed in systems of cold, trapped ions.

The first publication listed above proposed a new technique for generating native two-dimensional interactions for trapped-ion quantum simulations. It demonstrated a new ion trap geometry within which it is possible to confine ions in a self-assembled two-dimensional (2D) geometry, with concomitant 2D spin-spin interactions. This publication opened the way to investigating the physics of frustrated materials, highly entangled states, mechanisms underpinning high-temperature superconductivity, and other topics inaccessible to current one-dimensional systems.

The second publication listed above showed theoretically that by modulating the spin-spin interactions of an Ising model in time, a many-body interaction arises that leads to string order rather than the conventional magnetic order. Such string order is a common feature of symmetry protected topological states (such as the Haldane phase); we showed that it can be generated in a trapped ion quantum simulator device using standard trapping and laser technology.

In the third paper listed above, we proposed the first method for realizing fully-tunable Heisenberg-type interactions within standard ion traps. The Heisenberg model is one of the most important and interesting Hamiltonians in the field of quantum many-body physics, yet no ion-trap quantum simulation has implemented this model to date. Our proposal will be key for exploring the phase diagram of this model in a quantum simulator device, and is likely a precursor to realizing the first spin-liquid state in a controllable ion-trap system.

Experimental Apparatus

Starting from an empty room, our team dedicated 2+ years to construct a full-fledged ion trapping apparatus. The primary components of our apparatus are the (1) laser systems and optical beampaths, (2) vacuum system, and (3) ion trap, each of which are described in more detail below.

Optical beampaths and lasers

Four different laser systems are required for trapping and manipulating Yb+ ions, and a fifth serves as an optical reference for frequency stabilization. Part of our effort during the initial two years of work was to gain full control over the amplitudes, beam sizes, and beam profiles for all lasers.

The most important laser for trapping, cooling, and detecting Yb+ ions has a wavelength near 369nm. This system was acquired from M-squared, and achieves its target wavelength by frequency-doubling the output of a Titanium:Sapphire laser. Due to the large power output of the Titanium:Sapphire laser, as well as the high doubling efficiency, this system has achieved as much as 1 Watt of power at 369 nm.

The 369 nm beampath must be split into five different arms, each of which have their frequencies modified by acousto-optic (AO)- and electro-optic (EO) modulators, before being recombined. The AO modulators modify the frequencies in these different arms by up to 400 MHz compared to the input frequency, while EO modulators add sidebands at 2.1 GHz and 14.7 GHz. These frequency components are necessary for Doppler Cooling, ion recapturing, optical pumping, and resonant fluorescence detection in 171Yb+ ions.

In addition to the 369 nm laser, we also have diode laser systems at 935 nm and 399 nm, which are responsible for repumping and photoionization, respectively. The diode lasers and controllers have been purchased from Moglabs. For each of these systems, the laser light is fiber coupled to a High-Finesse wavemeter, to a frequency-stabilization breadboard, and to the ion trap itself. In addition, the 935 nm laser light passes through a 3 GHz fiber EOM before being sent to the trap.

Coherent manipulation and entanglement generation is accomplished by irradiating the ions with carefully-tailored pulses of 355 nm laser light. Since the entanglement speed is proportional to the square of the laser intensity, we have purchased and installed an 8 Watt laser for this purpose (Coherent Paladin Advanced 355-8000). The laser output is split into two parallel arms, each of which has its frequency manipulated by a dedicated AOM so that we can drive Raman transitions.

The beams are propogated to the trap in free-space; best-form lenses just outside the vacuum windows focus the beams to a 100 micron waist at the center of the ion trap.

The 369 nm, 399 nm, and 935 nm beams require active frequency stabilization to remain near the desired atomic transitions. (The 355 nm laser is pulsed, with a 100 GHz bandwidth, so no stabilization is required). Since a typical atomic transition in Ytterbium is 20 MHz wide, it is ideal to have lasers stabilized at the few-MHz level. This is accomplished using a custom PID feedback board, which sends a control voltage back to the laser controller to adjust the laser frequency. This system has been able to robustly lock our lasers for hours, keeping the desired frequency within a few MHz of the target at all times.

Vacuum System

Ultra-high vacuum (pressure < 10^{-9} Torr) is a de-facto requirement for isolated atomic quantum systems, since collisions with background gas molecules can destroy quantum information. To this end, we have carefully constructed a vacuum chamber and demonstrated its pressure to be <10^{-11} Torr (lower than our ion gauge can measure).

To achieve this result, we adapted several common ultra-high-vacuum techniques for our own purposes. First, all stainless-steel chamber components were “pre-baked" in air at 400° C for 24 hours, forming an oxide layer to inhibit hydrogen outgassing. After assembly, the system was initially pumped by a scroll-backed turbomolecular pump until the attached ion gauge measured below 10^{-6} Torr. The entire system was then wrapped in heater tape and baked at 200° C for 2 weeks, driving out adsorbed water and other gases throughout the chamber. During this process, we also activated the non-evaporable getter (NEG) pump, which provides a fast sorb for Hydrogen gas. Once the pressure dropped below 5 x 10^{-8} Torr, we turned on the attached ion pump and closed the valve to the turbomolecular pump. Pressures of <10^{-11} Torr were finally reached after we slowly brought the chamber back to room temperature.

The ion trap itself is mounted in a spherical-cube cell with optical access on 3 sides. The vacuum windows have applied anti-reflection coatings at 369 nm and 355 nm, to minimize back-reflections from laser beams that will be sent to the trap. Inside the cell, we use only ultra-high vacuum compatible materials for mounting, insulation, and electrical connections. The ion trap blades require 2 radio-frequency and 8 dc connections, which are made by mechanically fastening kapton-coated wires between to the vacuum feedthroughs and electrodes. Electrical connections to two atomic source ovens, which provide the Ytterbium atoms for ionization, are made in a similar manner. All wiring is strain-relieved and routed through the cell so as to not interfere with optical access.

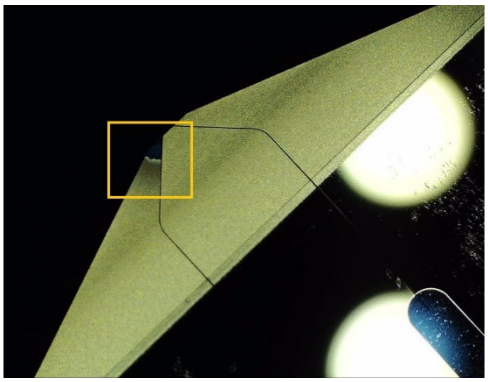
Ion Trap

In February 2019, despite well-functioning laser and vacuum systems, my lab had not yet achieved its first trapped ion signal. After confirming that laser frequencies were well-stabilized and calibrated, alignments were accurate, and that our imaging system was performing as designed, and observing neutral atom fluorescence within our chamber, we narrowed the problem to the ion trap itself.

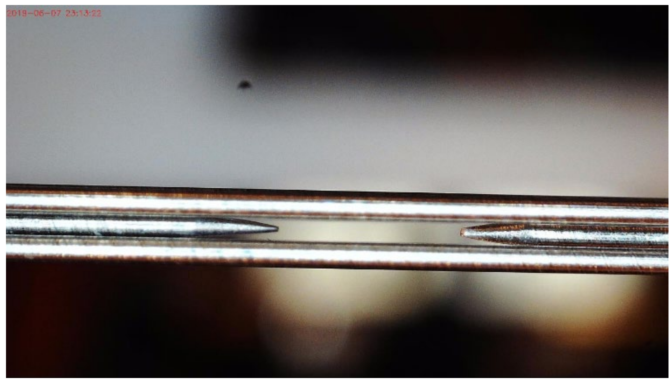
Our ion trap confines charged particles by the application of voltages to electrodes. In our original trap construction, the electrodes were fabricated by evaporating a thin layer of gold onto a machined fused-silica substrate.

What we discovered in Spring 2019 was that these electrodes were losing their evaporated gold layer in the presence of the large voltages required for ion trapping. A picture below (top left) shows a post-analysis of the electrode structures, with gold completely evaporated from one of the "endcap" electrode segments. Without voltage applied in this region, ions would always find an escape from the trap, making trapping impossible.

We therefore decided to build a simpler trap: one that is traditionally used for the trapping of 1D ion chains (top right picture below). This trap consists of all-stainless-steel electrodes: 4 parallel rods to provide radial ion confinement, and two "needle" endcaps for axial confinement.

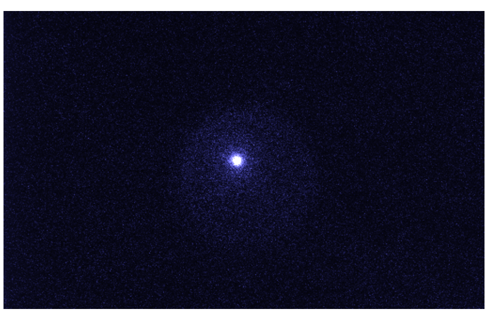


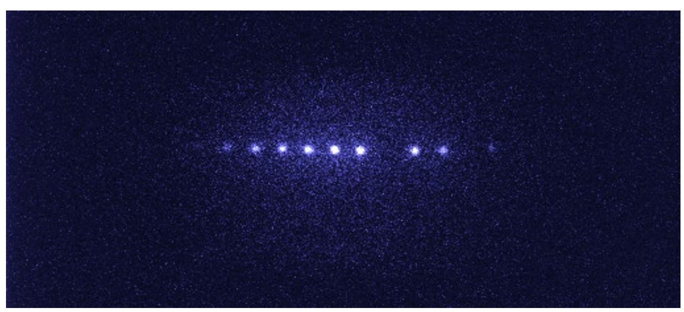
Missing gold on the electrode tip, caused by evaporation in the presence of large radio-frequency voltages



Close-up view of the replacement trap, fabricated from four parallel stainless-steel rods and two "needle"-type electrodes. The gap between parallel rods is 500 micron.

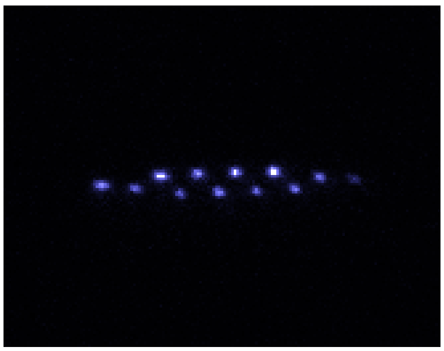
After fabricating this new ion trap and installing it within a new vacuum system, we were quickly able to see our first ion signals in early summer 2019. Although quantum information experiments would eventually need to trap isotope Yb-171, we started by trapping Yb-174 since its zero nuclear spin leads to much simplified trapping. Initial signals, showing a single ion and a chain of ions is pictured below. (Incidentally: in the chain picture, the "dark" ion is a different isotope of Yb, which is not resonant with the applied laser frequencies due to the isotope shift). Typical ion spacings are approx. 5 micron.

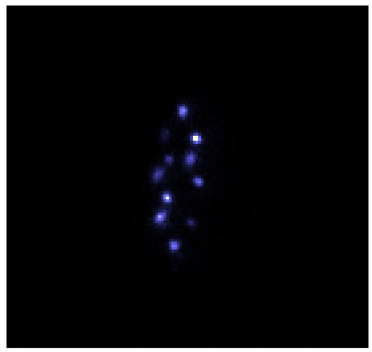


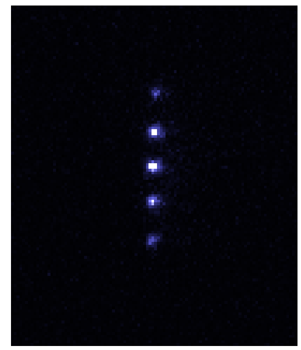


Following the stable trapping of Yb-174, we proceeded to trap Yb-171; this requires the application of a magnetic field, 3 additional laser frequencies, and control over the polarization of all laser light entering the trap. In addition, the Yb-171 isotope fluoresces only with 1/3 the brightness of Yb-174, requiring us to more carefully model and improve our fluorescence collection optics to maintain good signal-to-noise.

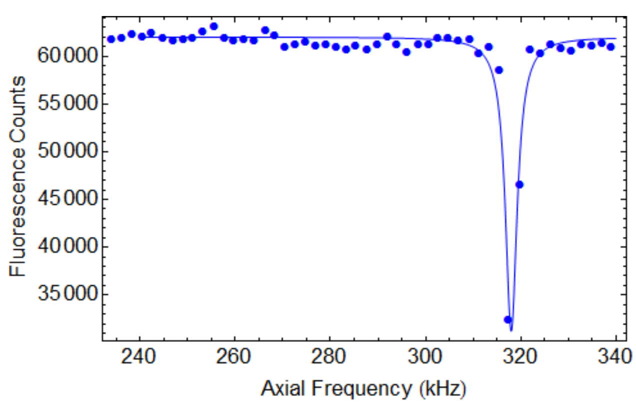
Our stainless-steel rod trap was designed so that we could control the shape of the ion crystal by changing the voltages applied to the "needle" electrodes. Specifically, by increasing the "needle" voltage, we can force the crystal to undergo a series of structural phase transitions, from 1D chain to a "zigzag" configuration, then to a 3D helix, then finally (at the highest applied voltages), a 2D crystal in the radial plane. The pictures below show a series of these phase transitions. Note that the 2D plane in the final image is shown from the side, so it appears as a single vertical plane. Note also that some ions in the 2D plane appear brighter than others; this is because there is depth to the image, and some are slightly defocused from the focal point of our imaging lens system.





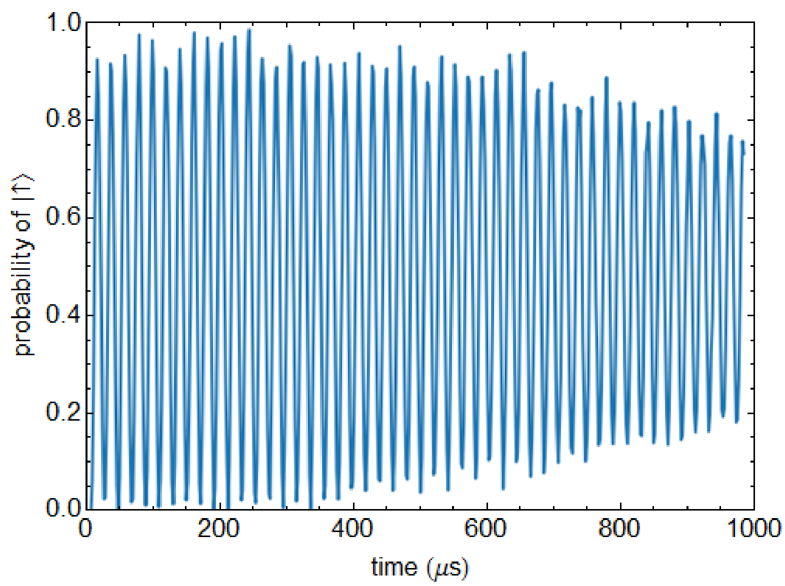


Since we want to perform quantum simulations using the 2D crystal configuration, and since no other group in the world has worked with this type of crystal, the first step is to characterize its structure and vibrational frequencies. These measurements are precursors for designing or understanding any quantum simulation, since the crystal vibrations themselves are what carry quantum information between the individual ion sites. Camera images give direct access to the ion positions; a different technique is needed to measure the vibrational frequencies. We apply a small radio-frequency (rf) voltage to one of the trap electrodes and measure the ion fluorescence as a function of rf frequency. When the frequency is resonant with a vibrational mode of the crystal, the ions (1) absorb energy, (2) heat up, (3) and are no longer resonant with the laser light. This leads to an observable decrease in fluorescence, showing the crystal resonances:



Prediction of these crystal resonances requires detailed theory calculations that takes into account the periodic voltage used to drive the ion trap. (1D ion calculations need only the time-averaged potential to correctly predict the crystal behavior). Numerical simulation work in my group is ongoing, and we soon expect to compare our measured crystal frequencies with our theoretically predicted values.

Additional measurements have established the long-term quantum coherence of the 2D crystals by observing Rabi oscillations. In these experiments, all ions in the crystal are initially prepared in the "down" quantum state of a 2-state system. Microwaves resonant with the 2-level energy splitting are used to drive the system from "down" to "up" and back again. At generic times, the system is in a quantum superposition of both "up" and "down". Repeating the experiment for multiple cycles gives a measure of the length of time over which quantum coherence can be maintained.



Future data using this trap will measure the heating rates of the 2D crystal due to the presence of the periodic trap voltage, and the lifetime of the 2D crystal itself in the absence of dispersive cooling mechanisms (which cannot be present during a quantum simulation).

One drawback of the "needle" trap design is that we do not have the optical access to view the 2D crystal perpendicular to the plane, since the "needles" are in the way. Our original trap design had open ends, but suffered from the problem of gold evaporation. We are currently fabricating a replacement trap with open ends made from solid tungsten. Tungsten has an exceptionally high melting point (to help prevent evaporation), low resistivity, and can be machined to high tolerance using wire-EDM techniques. We have therefore been manufacturing tungsten electrodes for a future iteration of the trap, which we anticipate will come on-line early next year.