

17 + NACTI

1st North American Conference on Trapped Ions

August 14 - 18, 2017

Boulder, CO



NIST
National Institute of
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U.S. Department of Commerce

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Timetable

Monday, August 14

0800–0900	Registration
0900–0930	<i>Welcome + opening of the meeting</i>
0930–1000	Samuel Fayer Harvard University <i>Testing the standard model and its symmetries</i>
1000–1030	Marianna Safronova University of Delaware and JQI <i>Laser cooling of negative ions</i>
1030–1100	Break
1100–1130	Daniel N. Gresh JILA <i>A precision measurement of the electron's electric dipole moment using trapped molecular ions</i>
1130–1200	David Hanneke Amherst College <i>Nonpolar molecular ions for precision measurements</i>

1200–1230	Ekkehard Peik PTB <i>Trapped ion optical clocks and tests of the equivalence principle</i>
1230–1400	Lunch
1400–1430	Boerge Hemmerling University of California, Berkeley <i>Quantum simulation of spin-bath dynamics with trapped ions</i>
1430–1500	Paul W. Hess JQI and Middlebury College <i>Quantum simulation of spin models, from adiabatic evolution to dynamics</i>
1500–1530	Christine Maier IQOQI and University of Innsbruck <i>Recent experiments on a trapped-ion quantum simulator</i>
1530–1600	Break
1600–1800	Poster Session 1

Tuesday, August 15

- 0900–0930 | Fabian Wolf
PTB and Leibniz University of Hannover
Quantum logic with molecular and highly-charged ions
- 0930–1000 | Kenneth R. Brown
Georgia Institute of Technology
CaH⁺ spectroscopy in a Coulomb crystal
- 1000–1030 | Chin-wen (James) Chou
NIST, Boulder
Preparation and coherent manipulation of pure quantum states of a single molecular ion
- 1030–1100 | Break
- 1100–1130 | Ania Kwiatkowski
TRIUMF and University of Victoria
Trapping radioactive ions for experimental nuclear physics at TRIUMF
- 1130–1200 | Christopher Izzo
Michigan State University
and National Superconducting Cyclotron Laboratory
Mass measurements of rare isotopes with LEBIT
- 1200–1230 | Joseph N. Tan
NIST, Gaithersburg
Experiments at NIST with highly ionized atoms in compact traps

1230–1400	Lunch
1400–1430	Tanja E. Mehlstaeubler PTB <i>Development of a multi-ion clock</i>
1430–1500	Peter D. D. Schwindt Sandia National Laboratories <i>Development of trapped Yb ion clocks</i>
1500–1530	Roland Wester University of Innsbruck <i>Collisions and terahertz spectroscopy of cold molecular ions</i>
1530–1600	Pavol Jusko University of Cologne <i>Low and higher resolution molecular spectroscopy in cold ion traps</i>
1600–1630	Break
1630–1800	JILA Lab Tours or Mesa Hike

Wednesday, August 16

- | | |
|-----------|--|
| 0900–0930 | John Chiaverini
Lincoln Laboratory and MIT
<i>Strategies for mitigation of trapped-ion motional heating</i> |
| 0930–1000 | Matthew G. Blain
Sandia National Laboratories
<i>Microfabrication of ion traps for quantum science</i> |
| 1000–1030 | Kyle S. McKay
NIST, Boulder
<i>Using surface science to understand the anomalous heating of trapped ions</i> |
| 1030–1100 | Break |
| 1100–1130 | Kunihiro Okada
Sophia University
<i>A laboratory study of interstellar ion-polar molecule reactions</i> |
| 1130–1200 | Neville J. A. Coughlan
University of Oxford
<i>Gas-phase ion-neutral reactions in Coulomb crystals</i> |
| 1200–1230 | Heather J. Lewandowski
JILA
<i>Controlled ion chemistry</i> |

1230–1400 | Lunch

1400–1430 | Ian Counts

MIT

Tuning friction between trapped ions and an optical lattice

1430–1500 | Paul C. Haljan

Simon Fraser University

Towards quantum double-well dynamics of trapped ion crystals near a structural phase transition

1500–1530 | Phil Richerme

Indiana University

Quantum simulation of 2D spin systems using trapped ions

1530–1600 | Break

1600–1800 | Poster Session 2

1800– | Conference Dinner at NCAR

Thursday, August 17

0900–0930	Norbert M. Linke JQI <i>Fault-tolerant quantum error detection on a programmable ion trap quantum computer</i>
0930–1000	Jungsang Kim Duke University <i>Technology for scaling trapped ion quantum computing with $^{171}\text{Yb}^+$ Ions</i>
1000–1030	Esteban A. Martinez University of Innsbruck <i>Quantum information processing with trapped ions in Innsbruck</i>
1030–1100	Break
1100–1130	Murray D. Barrett Center for Quantum Technologies and National University of Singapore <i>Progress towards an optical clock using $^{176}\text{Lu}^+$</i>
1130–1200	Geoffrey P. Barwood National Physical Laboratory <i>Recent measurements on single trapped Yb^+ and Sr^+ ion clocks</i>
1200–1230	David B. Hume NIST, Boulder <i>Reducing time dilation uncertainty in the NIST Al^+ optical clocks</i>

1230–1400	Lunch
1400–1430	Jonathan Home ETH Zürich <i>Sequential quantum measurements on trapped ions</i>
1430–1500	Peter Maunz Sandia National Laboratories <i>High-fidelity qubit operations in microfabricated surface ion traps</i>
1500–1530	Charles H. Baldwin NIST, Boulder <i>Joint quantum state and measurement tomography with incomplete measurements</i>
1530–1600	Break
1600–1630	Isaac Chuang MIT <i>Quantum signal processing for trapped ion qubit metrology</i>
1630–1700	Kevin A. Gilmore NIST, Boulder <i>Amplitude sensing below the zero-point fluctuations with a two-dimensional trapped-ion mechanical oscillator</i>
1700–1800	Industry panel

Friday, August 18

- 0900–0930 | Richard C. Thompson
Imperial College London
Optical sideband cooling of ions in a Penning trap
- 0930–1000 | Tomasz P. Sakrejda
University of Washington
Scaling to larger mixed species ion trap quantum computers; measurements of sympathetic cooling and normal mode coupling in trapped Ba-Yb chains
- 1000–1030 | David Hucul
UCLA
Laser-cooling and trapping the Goldilocks qubit: $^{133}\text{Ba}^+$
- 1030–1100 | Break
- 1100–1130 | Michael Drewsen
Aarhus University
Coherent internal state manipulation of single atomic and molecular ions by optical frequency combs
- 1130–1200 | Mark G. Kokish
Northwestern University
Quantum state preparation and detection of a single molecular ion using a quasi-cycling transition

1200–1230	Prateek Puri UCLA <i>Quantum chemistry and non-equilibrium thermodynamics in an atom-ion hybrid trap</i>
1230–1400	Lunch
1400–1430	Creston D. Herold Georgia Tech Research Institute <i>Measuring and modeling noisy gates</i>
1430–1500	Thomas P. Harty University of Oxford <i>Microwave-driven quantum logic with trapped ions</i>
1500–1530	David T. C. Allcock NIST, Boulder <i>Trapped-ion quantum logic with near-field microwave-driven gates</i>
1530–1600	Break
1600–1830	NIST Lab Tours

Talk abstracts

Monday, August 14, 0930-1000

Testing the standard model and its symmetries

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The Standard Model of particle physics is the great success and the great frustration of modern physics. It is very surprising that the Standard Model can successfully predict what is measured up to a part in 10^{12} , and yet be completely unable to explain why a universe could survive the big bang and why it should be made of matter rather than antimatter. Low energy experiments play a crucial role in testing the Standard Model of particle physics. Illustrations and aspirations will be presented.

Monday, August 14, 1000-1030

Laser cooling of negative ions

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Anion laser cooling holds the potential to allow the production of ultracold ensembles of any negatively charged species. The negative ion of lanthanum, La^- , was proposed as the best candidate for laser cooling of any atomic anion [1]. A very exciting application of La^- laser cooling includes cooling of antiprotons for antihydrogen formation and subsequent tests of CPT invariance, i.e. combined transformations of charge conjugation, spatial and time reversal, and weak equivalence principle [2]. A calculation of anion properties is a very difficult task, with complicated electronic structure of lanthanides presenting additional major problems. In this work, we present novel theoretical treatment of La^- ion and demonstrate an order of magnitude improvement of theoretical accuracy in comparison with previous calculations. Negative ion properties of importance to the realization of anion laser cooling are presented and critically evaluated for their accuracy.

[1] S. M. O'Malley and D. R. Beck, Phys. Rev. A **81**, 032503 (2010).

[2] A. Kellerbauer and J. Walz, New Journal of Physics **8**, 45 (2006).

Monday, August 14, 1100-1130

A precision measurement of the electron's electric dipole moment using trapped molecular ions

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The existence of a non-zero permanent electric dipole moment of the electron (eEDM) would have important implications for theories of physics beyond the Standard Model. To date no nonzero eEDM has been observed at presently achievable levels of experimental sensitivity. Trapped molecular ions offer high sensitivity to a measurement of the eEDM through long spin precession times and a large effective electric field enhancement while rejecting classes of systematic errors common to neutral beamline experiments. We will report on the first precision measurement of the eEDM using trapped molecular ions, where we demonstrate spin precession times of up to 700 ms in a HfF^+ ion cloud of a few tens of Kelvin. With our first generation experiment we have measured $d_e = (0.9 \pm 7.7_{\text{stat}} \pm 1.7_{\text{syst}}) \times 10^{-29} e \cdot \text{cm}$, corresponding to an upper bound of $|d_e| < 1.3 \times 10^{-28} e \cdot \text{cm}$ (90% confidence)[1]. This result provides independent confirmation of the current upper limit set by the ACME collaboration[2] in a unique experimental system sensitive to different systematic errors

than beam experiments. We will present the measurement technique and results as well as ongoing work to extend the measurement coherence time, to increase the total ion number, and to increase the experimental efficiency towards an order of magnitude increase in overall statistical sensitivity.

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[1] W. B. Cairncross *et al.*, arXiv:1704.07928 [physics.atom-ph].

[2] J. Baron *et al.*, *Science* **343**, 269 (2014).

Monday, August 14, 1130-1200

Nonpolar molecular ions for precision measurements

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Progress on techniques for quantum control of molecular ions will enable their application as precise probes of fundamental or exotic physics. Molecules that are nonpolar could have an important role in such experiments. They have a natural suppression of many systematic effects, including some ac Stark and blackbody radiation shifts. Rovibrational transitions within an electronic potential are dipole-forbidden, leading to narrow lines and long state lifetimes. Several groups around the world are pursuing experiments with H_2^+ [1, 2] and N_2^+ [3, 4].

We will discuss the $^{16}\text{O}_2^+$ molecular ion as a candidate system. In addition to being nonpolar, this molecule has no nuclear spin and thus no hyperfine structure. In particular, we discuss prospects for using O_2^+ in searches for time-variation of the proton-to-electron mass ratio. The molecule's deep ground-state potential lends itself well to such measurements. It also possesses several high-sensitivity transitions that take advantage of an accidental degeneracy between vibrational states of different electronic potentials [5]. Systematic effects for quadrupole and two-photon transitions

look promising [6]. Estimates of systematic effects for the transitions in the degenerate vibrational states are underway.

We will discuss our experimental work with O_2^+ state-preparation via resonance-enhanced multiphoton ionization (REMPI) of O_2 , co-trapping with $^9Be^+$ coolant/logic ions, and prospects for future experiments.

This material is based upon work supported by the NSF.

- [1] S. Schiller *et al.*, Phys. Rev. Lett. **113**, 023004 (2014)
- [2] J.-Ph. Karr *et al.*, Phys. Rev. A **94**, 050501(R) (2016)
- [3] M. Germann *et al.*, Nature Phys. **10**, 820–824 (2014)
- [4] M. Kajita *et al.*, Phys. Rev. A **89**, 032509 (2014)
- [5] D. Hanneke *et al.*, Phys. Rev. A **94**, 050101(R) (2016)
- [6] M. Kajita, Phys. Rev. A **95**, 023418 (2017)

Monday, August 14, 1200-1230

Trapped ion optical clocks and tests of the equivalence principle

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The $^{171}\text{Yb}^+$ optical clock that is based on an extremely narrow electric octupole transition possesses a favorable combination of a low systematic uncertainty in the low 10^{-18} range, and a high sensitivity in quantitative tests of relativity and searches for violations of the equivalence principle, because of the strongly relativistic character of the $4f^{13}6s^2 F_{7/2}$ excited state. Two reference transitions for optical clocks can be used in $^{171}\text{Yb}^+$: Besides the $^2S_{1/2}(F=0) \rightarrow ^2F_{7/2}(F=3)$ electric octupole (E3) transition at 467 nm there is also the $^2S_{1/2}(F=0) \rightarrow ^2D_{3/2}(F=2)$ electric quadrupole (E2) transition at 436 nm. For a frequency standard with very small systematic uncertainty, the E3 transition is advantageous due to its significantly lower sensitivity to electric and magnetic fields[1]. The E2 transition can be used for an in situ analysis of frequency shifts. With quantitative knowledge about the relative field sensitivities, shifts of the E3 transition frequency can be corrected more accurately analyzing changes in the E2 transition frequency in the same ion than by measuring the field-induced shifts on the E3 transition frequency directly. Measurements of the E3/E2 frequency ratio in different traps provide a consistency check on the control of

several systematic shifts, like the light shift produced by the thermal radiation field inside the ion trap or the Stark and Doppler shifts from uncompensated micromotion.

In comparisons and optical frequency ratio measurements of the $^{171}\text{Yb}^+$ E3 single-ion clock and a ^{87}Sr optical lattice clock at PTB we have performed improved tests for a temporal drift of the fine structure constant, for its coupling to the solar gravitational potential, and of a violation of Lorentz invariance in the electron sector. For these three cases, previous limits from clock-based experiments could be made more stringent by about an order of magnitude.

- [1] N. Huntemann, C. Sanner, B. Lipphardt, Chr. Tamm, E. Peik, *Phys. Rev. Lett.* **116**, 063001 (2016)

Monday, August 14, 1400-1430

Quantum simulation of spin-bath dynamics with trapped ions

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Chains of trapped ions are an ideal platform for studying the dynamics of qubits coupled to bosonic environments. This kind of dynamics is of interest in many problems in physics and biology such as charge transport, photosynthesis, and olfaction. In a chain of N trapped ions, an experimenter has access to an environment of the $3N$ vibrational modes of the chain, allowing for the simulation of very large vibrational environments with tunable spectral properties. In addition, the ions also serve as qubits, and both qubit-qubit and qubit-bath interactions can be engineered via quantum gates. Here, we discuss recent experimental results investigating spin-bath dynamics in ion strings. We explore the dynamics as the spin-bath coupling is varied, as well as when

the thermal occupation and quantum state of the environment are varied. We find that the quantized bath can assist in the transfer significantly and that the transfer efficiency depends on the baths' spectral structure and its temperature.

Monday, August 14, 1430-1500

Quantum simulation of spin models, from adiabatic evolution to dynamics

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Linear arrays of trapped and laser cooled atomic ions ($^{171}\text{Yb}^+$) are a versatile platform for studying strongly-interacting many-body quantum systems. By driving sideband interactions far-detuned from the motional mode spectrum, we generate long-range spin-spin interactions, which are largely insensitive to the number of ions in the trap. This allows us to study frustrated quantum magnetism in large system of up to 50 ions with single-site spatial resolution. We achieve a higher degree of control with a tightly-focused laser beam that imparts a unique light shift on each ion. By dynamically manipulating both the global and local laser interactions, we can perform experiments where the system Hamiltonian is adiabatically ramped [1], rapidly quenched [2], or periodically modulated [3]. These techniques are used to study topics of interest in condensed matter physics, such as phase transitions or the emergence of thermalization in

closed quantum systems. In particular, I will discuss recent results where trapped ions are used to realize spin models that exhibit a lack of thermalization, heralded by memory of initial conditions in their long-lived out-of-equilibrium dynamics [4]. Examples include many-body localization [5], prethermalization [6], and discrete time crystals [7]. I will also discuss experiments exploring a new type of dynamical phase transition, and our efforts towards scaling up system sizes to even more trapped ion spins using a cryopumped vacuum chamber.

- [1] R. Islam *et al.*, *Science* **340**, 583 (2013)
- [2] P. Richerme *et al.*, *Nature* **511**, 198 (2014)
- [3] C. Senko *et al.*, *Science* **345**, 430 (2014)
- [4] P. W. Hess *et al.*, arXiv: 1704.02439 (2017)
- [5] J. Smith *et al.*, *Nat. Phys.* **12**, 907 (2016)
- [6] B. Neyenhuis *et al.*, arXiv: 1608.00681 (2016)
- [7] J. Zhang *et al.*, *Nature* **543**, 217 (2017)

Monday, August 14, 1500-1530

Recent experiments on a trapped-ion quantum simulator

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In this talk I will present three recent experiments performed on our trapped-ion quantum simulator in Innsbruck. In our system spin-1/2 particles are encoded into the electronic states of a string of trapped ions, with laser beams used to generate variable-range effective spin-spin interactions and single-spin control.

Firstly, I will present the experimental application of Matrix Product State tomography, a tool to accurately estimate and certify the states of a broad class of quantum systems with an effort that increases efficiently with the number of constituents [1]. We use this technique to reconstruct entangled states of up to 14 individually controllable spins.

Secondly, I will present a study of dynamical quantum phase transitions (DQPTs) in our system [2]. We investigate and measure DQPTs in a string of ions simulating interacting

transverse-field Ising models. During the non-equilibrium dynamics induced by a quantum quench, we show the direct detection of DQPTs by revealing non-analytic behavior in time for strings of up to 10 ions. Moreover, we provide a link between DQPTs and entanglement production.

Finally, I will discuss experimentally observed excitation transport in a spin-hopping quantum system of up to 10 ions [3]. The transport efficiency is investigated under the influence of engineered single-site static disorder as well as dynamic dephasing. We observe localization or suppressed spread of an initial single excitation under strong, tunable static disorder. Moreover, we demonstrate that localization can be lifted when adding telegraph-like dephasing to the system.

- [1] B. P. Lanyon, C. Maier, *et al.*, arXiv:1612.08000 (2016), accepted by Nature Physics
- [2] P. Jurcevic, *et al.*, arXiv:1612.06902 (2016), accepted by Phys. Rev. Lett.
- [3] C. Maier, *et al.*, in preparation

Tuesday, August 15, 0900-0930

Quantum logic with molecular and highly-charged ions

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Quantum logic spectroscopy is a powerful technique to investigate previously inaccessible species that lack a strong cycling transition for cooling and state detection. In my presentation, I will describe how quantum logic techniques can be employed to non-destructively detect the state of a molecular ion, including the observation of quantum jumps between rotational states. The scheme is based on sensing via the logic ion small state-dependent oscillating optical dipole forces acting on the molecule [1]. The state detection efficiency is limited by residual off-resonant scattering and can be improved by employing Fock states of motion with a force sensitivity of around $100\text{yN}/\sqrt{\text{Hz}}$. Compared to e.g. Schrödinger cat or squeezed motional states, Fock states offer improved sensitivity in all quadrature components. This is demonstrated by quantum-enhanced probing of small displacements and the phase evolution of a displaced Fock state.

In the future, we plan to extend quantum logic spec-

troscopy to highly-charged ions that are promising candidates for optical clocks and the search for a variation of fundamental constants. First results on a cryogenic Paul trap setup at PTB with beryllium ions as the logic ion species will be presented.

[1] F. Wolf *et al.*, Nature **530** 457 (2016)

Tuesday, August 15, 0930-1000

CaH⁺ spectroscopy in a Coulomb crystal

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We perform multi-photon dissociation spectroscopy on CaH⁺ in a Coulomb crystal of laser-cooled Ca⁺. The dissociation yields Ca⁺ and H which can be readily observed by laser-induced Ca⁺ fluorescence. Using a pulsed mode-locked laser, we were able to observe two vibrational overtones of CaH⁺ [1] and vibronic spectra for CaH⁺ [2] and CaD⁺ [3]. A comparison of the CaH⁺ and CaD⁺ spectra reveals that theoretical models using a frozen core for Ca⁺ underestimate the electronic transition energy from $1^1\Sigma$ to $2^1\Sigma$ by 700 cm^{-1} . By pulse shaping the mode-locked laser, we have been able to obtain rovibronic spectra of this transition. We will conclude by discussing prospects for using these transitions for themometry and quantum logic spectroscopy.

- [1] N. B. Khanyile, G. Shu, and K. R. Brown, Nat. Commun. **6**, 7825 (2015)
- [2] R. Rugango, A. T. Calvin, S. Janardan, G. Shu, and K. R. Brown, ChemPhysChem **17**, 3764 (2016)
- [3] J. Condoluci, S. Janardan, A. T. Calvin, R. Rugango, G. Shu, K. R. Brown, arXiv:1705.01326

Tuesday, August 15, 1000-1030

Preparation and coherent manipulation of pure quantum states of a single molecular ion

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We demonstrate quantum control of a single molecular ion via quantum logic spectroscopy [1]. In our experiment, we drive the motional sidebands of Raman transitions in a molecular ion and detect the resulting excitation of the secular motion with a co-trapped atomic ion. This measurement projects the molecule into a pure internal state. The state of the molecule can subsequently be coherently manipulated, as demonstrated by Rabi oscillations between magnetic sub-levels of rotational states in either the same or distinct rotational manifolds. We use one continuous-wave laser and one frequency comb [2], both far off-resonant from molecular transitions, to manipulate the molecule. This makes our approach applicable to coherent control and precision measurement of a vast number of molecular ion species.

This work was supported by the US Army Research Office and the NIST quantum information program. C. Kurz acknowledges support from the Alexander von Humboldt

foundation. P. N. Plessow acknowledges support by the state of Baden-Württemberg through bwHPC.

[1] C. W. Chou et al., *Nature*, 545, 203 (2017).

[2] D. Leibfried, *New J. Phys.* 14, 023029 (2012).

Tuesday, August 15, 1100-1130

Trapping radioactive ions for experimental nuclear physics at TRIUMF

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Ion traps were first deployed at rare-isotope-beam (RIB) facilities for Penning trap mass spectrometry roughly 30 years ago. The technique is of growing popularity, with existing or planned ion traps at all world-class RIB facilities. Ion traps for beam preparation may reduce backgrounds by bunching or purifying the RIB. Trap-assisted or in-trap nuclear decay spectroscopy allows for investigations of nuclear structure and for investigations of astrophysically important highly charged ions; the latter would be impossible with traditional techniques. The single-ion sensitivity combats low production yields, leading to single-ion mass spectrometry needed for studies of nuclear structure and fundamental interactions.

TITAN at TRIUMF (Vancouver, Canada) exemplifies ion trapping at RIB facilities. Four traps can be operated individually or together for precision mass spectrometry and in-trap decay spectroscopy. The Collaboration is pioneering the use of highly charged ions for experimental nuclear physics via beam production and purification. To that end, a fifth trap is

under development to cool highly charged radioactive ions with electrons. I will discuss techniques used at TITAN and present highlights from the mass-measurement and decay-spectroscopy program.

Tuesday, August 15, 1130-1200

Mass measurements of rare isotopes with LEBIT

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One of the most fundamental properties of an atomic nucleus is its mass. The mass defect corresponds to the nuclear binding energy, and thus precise mass measurements of rare isotopes may be used to study the important role of nuclear binding in several areas including nuclear structure, astrophysics, and fundamental interactions. Penning trap mass spectrometry (PTMS) has proven to be the most precise technique for measurements of atomic masses. The Low-Energy Beam and Ion Trap (LEBIT) experiment at the National Superconducting Cyclotron Laboratory has successfully employed PTMS for numerous measurements of exotic nuclei, providing valuable insights into the physics of atomic nuclei far from stability. Additionally, the Single Ion Penning Trap (SIPT) is nearing completion at LEBIT. This highly sensitive cryogenic Penning trap will extend the reach of LEBIT further from stability, allowing measurements of extremely rare isotopes produced at very low rates.

Tuesday, August 15, 1200-1230

Experiments at NIST with highly ionized atoms in compact traps

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Applications of weakly allowed transitions in highly ionized atoms are familiar in astronomy and spectroscopic diagnostics. More recent are revelations of the existence of atomic states that are potentially advantageous for improving the determination of fundamental constants [1], tightening constraints on possible time-variation of the fine-structure constant α [2], developing novel optical atomic clocks [3], and exploring quantum information processes with greater immunity to decoherence [4]. With the notable exception of one-electron ions in Rydberg states[1], computations for the spectroscopic properties of such many-electron systems are not very accurate due to severe cancellations between the nearly-degenerate levels of interest (an essential feature); hence, experimental exploration is necessary. For one-electron ions, on the other hand, the theory is simpler and predictions are very precise; in fact, the uncertainties for high-L Rydberg states are limited by the precision of the atomic fundamental constants, thus opening the possibility for new determinations if such systems are realized [1]. Of particular interest are the Rydberg constant and the fine-

structure constant because of their important roles in the anticipated revision of the International System of Units (SI) to one defined entirely by fundamental constants. It is desirable to augment the diversity of measurements contributing to the determination of such crucial constants of nature. This talk presents experiments using highly charged ions extracted from the electron beam ion trap (EBIT) at NIST. To make one-electron ions in Rydberg states, fully-stripped ions (Ne^{10+}) are captured in a compact Penning trap with an intersecting beam of rubidium atoms for charge transfer. To optimize the production of ions with low ionization threshold, as may be needed to explore the aforementioned applications, a miniature EBIT has been built with features designed for compensating the larger space charge effects in an electron beam propagated at low energies.

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Tuesday, August 15, 1400-1430

Development of a multi-ion clock

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Optical atomic clocks based on trapped ions or neutral atoms, have both reached a relative inaccuracy of a few 10^{-18} in laboratories today. While neutral lattice clocks have a superior short-time stability operating several 1000s of atoms and thus can work at extremely short integration times, ion clocks have a high potential to achieve lowest inaccuracies with well-controlled single atomic particles. In 2011, we proposed to build a multi-ion clock which can be a promising and combining path to profit best from both worlds [1]. Challenges are to control the complex dynamics of ion Coulomb crystal to a high degree. Based on our scalable trap design and a benchmarked prototype trap, we developed a high-precision ion trap at PTB, which has the capability to control ensembles of small trapped linear strings of ions in a one-dimensional array, so that about 100 ions can be interrogated simultaneously. We show the experimental characterization of our chip-based linear Paul trap and present an estimated error budget of an In^+/Yb^+ multi-ion clock based on trapped ions in the new chip trap.

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Tuesday, August 15, 1430-1500

Development of trapped Yb ion clocks

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Over the last two decades, there has been a great deal of effort to miniaturize atomic clocks. While previous efforts have been focused on alkali vapor cell atomic clocks, frequency drifts associated with vapor cells have prompted research into the miniaturization of other atomic clock technologies. Here we present our work on the miniaturization of trapped ion clocks. We use the 12.6 GHz microwave transition of the $^{171}\text{Yb}^+$ ion for the clock. On the order of 100,000 ions are confined in a linear RF Paul trap, and a microTorr of a noble buffer gas cools the ions to ~ 1000 K. The isolation of the ions from the environment suffers little from the miniaturization of the ion trap and the surrounding vacuum package, providing long-term stability of the frequency of the ion clock in the 10^{-14} range. We will present results from miniaturizing the vacuum package containing the ion trap to 1 cm^3 . Recent work focuses on reducing the effects of the $^2F_{7/2}$ -state, where ions can get trapped during clock operation. Methane is used to collisionally quench the F -state. Finally, we present a new technique to implement the Yb ion clock, the alkali-mediated ion clock. To eliminate the need for a 369 nm laser, we introduce an alkali vapor to prepare and read out the state of the Yb ions. In this technique,

a laser resonant with the alkali prepares the state of alkali. Spin exchange collisions transfer spin polarization to the Yb ions. After microwave excitation of the Yb ions, their state is read out through their collisional effect on the alkali atoms, which in turn is read out with the alkali-resonant laser. We will discuss simulations and early experimental results of this approach.

Tuesday, August 15, 1500-1530

Collisions and terahertz spectroscopy of cold molecular ions

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Multipole ion traps are a versatile tool to confine molecular ions over long periods of time and to prepare and control their internal and translational degrees of freedom down to few Kelvin. We have shown that to investigate the rotational quantum states of negative molecular ions photodetachment spectroscopy is a useful technique [1]. Subsequently, we have used photodetachment spectroscopy to probe internal state-changing collisions of OH^- anions with neutral helium atoms at temperatures between 20 and 40 K [2, 3]. The same approach has allowed us to perform terahertz spectroscopy of rotational transitions in this molecular anions [4]. Recently we have applied near-threshold detachment spectroscopy to the triatomic molecular anion NH_2^- . A refined value of the electron affinity of NH_2 and measurements of the lowest two rotational transitions of this ion will be reported. These results will be discussed in light of searches for this negative ion in the interstellar medium [5].

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Tuesday, August 15, 1530-1600

Low and higher resolution molecular spectroscopy in cold ion traps

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Ion traps are a well known tool used in spectroscopy of ions. Unlike traditional spectroscopy schemes, the interaction of radiation with ions is being investigated by monitoring the ions, rather than the photons. So called “action spectroscopy” scheme like e.g. LIR (Laser Induced Reactions) for high- and IRPD (IR PreDissociation) for low-resolution spectroscopy in the IR are applied routinely in the cryogenic ion 22-pole trap instruments COLTRAP[1], and the FELion user station located at the FELIX Laboratory[2].

More recently, schemes providing access even to pure rotational transitions, i.e., exciting with very low photon energies, have been developed. Schemes based on rotational-state dependent He cluster growth at 4 K in the cryogenically cooled ion trap[3] and on double resonance IR-THz excitation[4], and their application to spectroscopy of light mass ions of astrophysical interest (e.g. isotopologues of H_3^+ , C_3H^+ [5, 6]) are going to be presented.

- [1] O. Asvany *et al.*, Appl. Phys. B. **114**, 203 (2014).
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- [4] P. Jusko *et al.*, Phys. Rev. Lett. **112**, 253005 (2014).
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Wednesday, August 16, 0900-0930

Strategies for mitigation of trapped-ion motional heating

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Anomalous motional ion heating, due to electric-field noise of unknown origin, is a limiting source of error in multi-qubit operations using ions confined to chip-scale trap arrays. Many approaches have been suggested to reduce ion heating, with varying degrees of applicability and effectiveness. Here we explore several methods to characterize and mitigate electric-field noise affecting trapped ions, with an eye toward simultaneously minimizing ion heating and system complexity. We will discuss ways to identify technical (non-surface) noise, the effect of trap electrodes material, and the utility of surface-preparation techniques, particularly in combination with lowering the temperature of the trap electrodes. The results of this work suggest that there are trade offs in reducing ion heating to acceptable levels that depend on desired capability and system constraints.

Wednesday, August 16, 0930-1000

Microfabrication of ion traps for quantum science

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Microfabricated ion traps offer potentially important advantages for both micro-mass-spectrometry and quantum information science. If properly engineered for the experimental objectives, these micro-devices offer the ability to extend the performance of their macroscopic equivalents, and can even allow new concepts to be explored in both classical and quantum physics and chemistry. One early example is the design and construction of a large array of micrometer-sized cylindrical ion traps for application as the mass analyzer for a micro-mass-spectrometer [1]. As a second example, the ability to fabricate complex and arbitrarily arranged two-dimensional trap electrode geometries and arrays has been recognized to be critical for a number of trapped ion quantum information experiments. In particular, surface electrode ion traps have enabled the ion trap charge coupled device architecture [1], whereby ions can be moved between different trapping regions optimized for ion loading and qubit initialization, entanglement, storage, and read-out. For this architecture, the ability to design and fabricate surface electrode traps that include junctions for the spatial re-ordering of ions [3] is essential. Precision through-chip holes for ion loading and photon collection/delivery,

arbitrarily shaped trap chips for increased optical access to the ions, and trap designs optimized for high voltage efficiency and low losses allow for realizing the required experimental features of the trap. Assembly and wiring of the chip and package are also critical for the subsequent rendering of a highly evolved, experiment-ready ion trap chip technology. Additionally, micro ion trap chip technologies may be interfaced to other micro-device technologies, for example diffractive optical elements (DOEs) or cavity mirrors, to allow for state read-out or coherent information transfer. This "micro-systems" approach to the design and integration of surface electrode ion trap devices relies on microfabrication and packaging techniques that have been optimized to the experimental application. [†]Sandia National Laboratories is a multitechnology laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

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Wednesday, August 16, 1000-1030

Using surface science to understand the anomalous heating of trapped ions

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Previous work has shown that in situ ion bombardment of ion trap electrodes can reduce the heating rates of trapped ions by two orders of magnitude [1]. We report on the use of surface science tools to investigate the specific changes to ion trap electrode surfaces as a result of surface treatments such as ion bombardment, in order to understand the root cause of anomalous heating in ion trap experiments. We use surface science tools and techniques, such as scanning probe microscopy, x-ray photoemission spectroscopy (XPS), and low energy electron diffraction (LEED), to study electrode surface morphology, contamination, crystallinity, and diffusion and then correlate these measurements with heating rate measurements of ion traps and ion trap electrode surfaces. We also report on heating rate studies using a stylus trap to study various proximal surfaces and surface treatments [2].

[1] D. A. Hite *et al.*, Phys. Rev. Let. 109, **103001** (2012)

[2] D. A. Hite *et al.*, MRS Advances (2017)

Wednesday, August 16, 1100-1130

A laboratory study of interstellar ion-polar molecule reactions

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Cold ion-molecule reactions are important to understand the synthesis of interstellar molecules and the chemical evolution in interstellar molecular clouds [1]. Particularly, ion-polar molecule reactions at low temperatures play important roles, because the ion-dipole capture rates are proportional to the inverse of the square-root of reaction temperature. Nonetheless, most of the reaction-rate constants compiled in the astrochemical databases are still the data measured at near room temperature [2]. Actually the reactions between ions and polar molecules have not been studied extensively in the laboratory due to condensation of polar gases at low temperatures. Moreover, the information of the reaction branching ratios is not sufficiently known. A new experimental method combining a sympathetic laser-cooling technique for generating cold molecular ions with a Stark velocity filter for producing cold polar molecules has a potential ability to achieve a systematic study cold ion-polar molecule reactions over the environmental temperatures in molecular clouds (10-100 K) [3, 4]. In the above context, we performed the reaction-rate measurements between the sympathetically cooled Ne^+ and N_2H^+ ions and the velocity-selected CH_3CN molecules at translational temperatures lower than 10 K [5, 6]. Recently we measured the reaction-rate constants

by supplying the rotationally cooled slow CH_3CN generated by a cooled gas nozzle, and obtained a result suggesting that the reaction-rate constants are determined by the rotational temperature of CH_3CN rather than the translational temperature. We will present the details of the experimental technique and discuss the rotational temperature effect on the reaction-rate constants. Additionally, we will present commissioning results of a new type of Stark velocity filter, labeled a wavy Stark velocity filter, which can widely change the translational and rotational temperatures of velocity-selected polar molecules without changing the output beam position. Combining a cryogenic linear Paul trap for rotational cooling of molecular ions with the wavy Stark velocity filter enables us to systematically study interstellar ion-polar molecule reactions over a wide range of reaction temperatures [7]. The status of our experimental projects will also be reported.

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- [2] D. McElroy *et al.*, *Astron. Astrophys.* **550**, A36 (2013).
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- [4] M. T. Bell *et al.*, *Faraday Discuss.* **142**, 73 (2009).
- [5] K. Okada *et al.*, *Phys. Rev. A* **87**, 043427 (2013).
- [6] K. Okada *et al.*, *Phys. Rev. Appl.* **4**, 054009 (2015).
- [7] K. Okada *et al.*, submitted to *Rev. Sci. Instrum.*

Wednesday, August 16, 1130-1200

Gas-phase ion-neutral reactions in Coulomb crystals

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Gas-phase ion-neutral reactions are a common feature in the chemistry of the interstellar medium, upper atmosphere, and combustion reactions. Thus, they are both interesting and important to understand. These reactions are conventionally thought of as being barrierless, where they proceed along a reaction coordinate without surmounting an activation energy barrier. In reality, these reactions proceed along complex reaction surfaces and can encounter submerged barriers. Further contrary to conventional wisdom, these reactions often display non-Arrhenius behaviour and their reaction rate constants increase at low temperatures, a phenomenon which is largely unexplained by current theories. Therefore, it is critical to experimentally probe these fundamental reactions at low temperatures to establish the validity of models describing complex ion-neutral reaction systems. Ultimately, we aim to achieve full state-selectivity for all reactant species by carefully controlling the reaction conditions.

Here, we employ a combination of trapping and deceleration techniques to generate cold ionic and neutral species, respectively. Calcium atoms are non-resonantly ionised and

the resulting Ca^+ ions are held in a linear Paul trap, where they are laser-cooled and form Coulomb crystals. Other ionic reactants, including molecular ions for which laser-cooling is not viable, may be co-trapped within the crystals and sympathetically cooled. The fluorescence continually emitted by the laser-cooled calcium ions is monitored in real time by a charge coupled device camera, from which the number of calcium ions in the crystal can be inferred. Neutral reactant species are decelerated by exploiting the Stark effect or are velocity-filtered in a bent quadrupole guide. The reactants are introduced into the ion-trap chamber where they react either with Ca^+ ions directly, or with co-trapped ionic species. The composition of each crystal at any given reaction time may be established by ejecting the entire crystal into an adjacent time of flight mass spectrometer. Using these techniques, we have successfully measured reaction rate constants for reactions involving atomic and molecular ions with a range of neutral reactant species at various temperatures.

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- [4] S. Willitsch, *Phys. Rev. Lett.* **100**, 043203 (1987)

Wednesday, August 16, 1200-1230

Controlled ion chemistry

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Radicals and ions frequently play an important role in gaseous media such as the Interstellar Medium (ISM) and the upper atmosphere. Although collisions in the ISM between ions and radicals are very rare events, the long timescales involved mean such reactions make important contributions to the pathways for assembly and destruction of complex chemical species. Unfortunately, experimental measurements of the rates and particularly the dynamics of reactions between ions and radicals are very few and far between. Our system overcomes some of the experimental challenges by using trapped molecular ions and Stark decelerated neutral radicals. Here, we can study reactions between molecules in single quantum states down to millikelvin temperatures. Our very high sensitivity allows us to study reactions where the reaction rate can be as low as one reaction per minute. We present first results from two systems (1) $\text{Ca}^+ + \text{NO}$ and (2) $\text{C}_2\text{H}_2^+ + \text{propyne}$ and allene.

Wednesday, August 16, 1400-1430

Tuning friction between trapped ions and an optical lattice

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Following theoretical proposals [1, 2, 3, 4], a trapped ion transported along a periodic optical-lattice potential is studied as a paradigmatic nanocontact frictional interface. With sub-lattice-site position resolution, we resolve individual *stick-slip* events, whereby an ion slips out of one lattice site and sticks into a new lower-energy site. To date, we have measured the reduction of friction between the lattice and a chain of ions through structural mismatch [5] and observed a structural phase transition known as the Aubry transition [6]. More recently, we have distinguished two regimes

of stick-slip friction: the *single-slip* regime, where an ion deterministically slips to the adjacent lattice site, and the *multislip* regime, where an ion stochastically slips to one of several available lattice sites. The velocity- and temperature-dependence of friction in both the single-slip [7] and multi-slip regimes [8] will be discussed.

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- [6] A. Bylinskii, D. Gangloff, I. Counts, V. Vuletić. *Nature Materials* **15**, 717-721 (2016).
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Wednesday, August 16, 1430-1500

Towards quantum double-well dynamics of trapped ion crystals near a structural phase transition

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In a linear radio-frequency Paul trap, relaxing the transverse confinement beyond a critical value will cause laser-cooled, trapped ions to undergo a symmetry-breaking structural transition from a linear to a two-dimensional zigzag configuration. I will discuss our current investigations of dynamics near this linear-zigzag transition at temperatures corresponding to a few quanta or less of thermal energy in the vibrations of the ion array. The second-order nature of the linear-zigzag transition, and the resulting double-well potential that develops as the critical point for the transition is crossed, offer the possibility to explore a variety of quantum effects, in particular tunneling phenomena near the critical point. We are ultimately interested to see whether superposition states of the zig and zag symmetry-broken configurations can be prepared, and how the decoherence of such states depends on the number of ions.

Wednesday, August 16, 1500-1530

Quantum simulation of 2D spin systems using trapped ions

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The computational difficulty of solving fully quantum many-body spin problems is a significant obstacle to understanding the behavior of strongly correlated quantum matter. This talk will describe progress towards the design and construction of a 2D quantum spin simulator to investigate physics currently inaccessible to 1D trapped ion systems [1]. The effective quantum spins will be encoded within the well-isolated electronic levels of $^{171}\text{Yb}^+$ ions and confined in a two-dimensional planar crystal within an rf Paul trap. The ions will be coupled via phonon-mediated optical dipole forces, allowing for study of Ising, XY, or Heisenberg spin-spin interactions [2]. The system is predicted to scale beyond 100+ quantum particles, while maintaining individual-ion control, long quantum coherence times, and site-resolved projective spin measurements. This versatile tool will serve as an important experimental resource for exploring difficult quantum many-body problems in a regime where classical methods fail.

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[2] A. Bermudez, L. Tagliacozzo, G. Sierra, and P. Richerme, Phys. Rev. B **95**, 024431 (2017)

Thursday, August 17, 0900-0930

Fault-tolerant quantum error detection on a programmable ion trap quantum computer

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Our experiment constitutes a programmable quantum computer based on five trapped $^{171}\text{Yb}^+$ ions. Individual addressing via an array of Raman laser beams combined with a pulse-shaping scheme involving all harmonic modes of motion creates entangling XX-gates between any pair of ions. Thereby the device provides a fully connected system of atomic clock qubits with long coherence times, and high gate fidelities. This quantum computer can be programmed from a high-level interface to execute arbitrary quantum circuits [1].

Quantum error correction codes are key to the idea of scaling up quantum computers to large sizes [2]. Showing that all elements of error correction can be realized in a fault-tolerant way is therefore of fundamental interest. Fault-tolerance removes the assumption of perfect encoding and

decoding operations of logical qubits.

We present the implementation of the $[[4,2,2]]$ code, an error detection protocol [3] which uses four physical qubits to encode two logical qubits, one of which can be made fault-tolerant by appropriate construction of the encoding and stabilizer circuits. Remarkably, it works with a bare ancilla qubit.

The results demonstrate for the first time the robustness of a fault-tolerant qubit to imperfections in the very operations used to encode it, as errors are suppressed by an order of magnitude. We present data to show that this advantage over a non-fault-tolerant qubit persists even in the face of both large added error rates and coherent errors. The residual errors are also below or at break-even level compared with the error probability of a single physical qubit [4].

Finally, we discuss our work towards scaling up this system via an integrated systems approach and photon-interconnects between distant modules.

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Thursday, August 17, 0930-1000

Technology for scaling trapped ion quantum computing with $^{171}\text{Yb}^+$ Ions

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Recent progress in trapped ion quantum information processing technology has led to a system-scale approach to designing compact ion trapping system suitable for a general-purpose quantum computation. In this talk, we present our system comprised of a linear chain of $^{171}\text{Yb}^+$ ions trapped in a microfabricated surface trap from Sandia. The qubit state is initialized and measured by illuminating the ions with resonant laser beams at 369.5nm [1]. The qubit gate operations are carried out using mode-locked pulsed laser at 355nm, where Raman transitions are driven by a single global beam (that illuminates the entire chain) and two independent individual addressing beams that are tightly focused onto single qubits in the chain [2]. The individual addressing beams can be steered across the ion chain, to realize a two-qubit gate between an arbitrary pair of ions in the chain. Our system is designed so that both single- and two-qubit gates can be applied in a way that the gate is independent of the optical phase of the Raman lasers. We will discuss the performance of the individual qubit operations such as qubit detection and the qubit gates, and discuss the prospect of running

complex quantum algorithms on our system.

[1] R. Noek *et al.*, *Opt. Lett.* 38, **4735** (2013)

[2] S. Debnath *et al.*, *Nature* 536, **63** (2016)

Thursday, August 17, 1000-1030

Quantum information processing with trapped ions in Innsbruck

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In this talk I will discuss two recent experiments on different experimental architectures. First, I will report on the experimental demonstration of a digital quantum simulation of a lattice gauge theory, by realizing $(1 + 1)$ -dimensional quantum electrodynamics (the Schwinger model) on a few-qubit trapped-ion quantum computer [1]. We are interested in the real-time evolution of the Schwinger mechanism, describing the instability of the bare vacuum due to quantum fluctuations, which manifests itself in the spontaneous creation of electron-positron pairs. To make efficient use of our quantum resources, we map the original problem to a

spin model by eliminating the gauge fields in favour of exotic long-range interactions, which can be directly and efficiently implemented on an ion trap architecture. We explore the Schwinger mechanism of particle-antiparticle generation by monitoring the mass production and the vacuum persistence amplitude. Moreover, we track the real-time evolution of entanglement in the system, which illustrates how particle creation and entanglement generation are directly related.

Then, I will discuss an experiment aiming towards scalable quantum computing, the eQual project, which uses an in-cryostat planar trap. Two ion species ($^{40}\text{Ca}^+$ and $^{88}\text{Sr}^+$) are trapped simultaneously, for sympathetic cooling and an extended computational toolbox. As a building block for more complex quantum computing algorithms involving ion shuttling and rearrangement, we perform physical swap operations on two ions. Based on experiments and numerical simulations of our trapping potentials, we seek to understand heating mechanisms and optimize these swap operations, for both the single-species and mixed-species cases.

[1] E. A. Martinez, C. A. Muschik *et al.*, *Nature* **534**, 516-519 (2016)

Thursday, August 17, 1100-1130

Progress towards an optical clock using $^{176}\text{Lu}^+$

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Singly ionized lutetium has been proposed as an optical clock candidate [1, 2]. It supports three clock transitions: a highly forbidden magnetic dipole (M1) transition $^1S_0 \leftrightarrow ^3D_1$ at 848 nm with an estimated lifetime of 172 hours [4], a spin-forbidden electric quadrupole (E2) transition $^1S_0 \leftrightarrow ^3D_2$ at 804 nm with a measured lifetime of 17.3 s [3], and an E2 transition $^1S_0 \leftrightarrow ^1D_2$ at 577 nm with a measured lifetime of 180 ms [3]. A technique of hyperfine averaging eliminates shifts arising from the electronic angular momentum [1], which realises an effective $J = 0$ to $J = 0$ transition. This provides a reference frequency with low sensitivity to electric and magnetic fields. A narrow electric dipole transition provides suitable detection and the possibility of a low Doppler cooling limit. The differential static scalar polarisability is expected to be sufficiently small for practical room temperature operation and potentially negative [3] which would allow micro-motion shifts to be eliminated. A negative value in particular is critical for realising a proposal for clock operation with large ion crystals [2].

We report clock operation on the $^1S_0 \leftrightarrow ^3D_1$ and $^1S_0 \leftrightarrow ^3D_2$ transitions of $^{176}\text{Lu}^+$. This has allowed precision spectroscopy of all levels relevant to practical clock operation. We will report our latest results towards the assessment of $^{176}\text{Lu}^+$ as a frequency standard, and measurement of the differential static polarisabilities. We will also discuss future prospects for multi-ion clock operation.

- [1] M. D. Barrett, *Developing a field independent frequency reference*, New J. Phys. **17**(5), 053024, (2015)
- [2] K. J. Arnold, *et. al.*, *Prospects for atomic clocks based on large ion crystals*, Phys. Rev. A. **92**, 032108, (2015)
- [3] E. Paez, *et. al.*, *Atomic properties of Lu^+* , Phys. Rev. A. **93**, 042112, (2016)
- [4] K. J. Arnold, *et. al.*, *Observation of the 1S_0 to 3D_1 clock transition in Lu^+* , Phys. Rev. A. **94**, 052512, (2016)

Thursday, August 17, 1130-1200

Recent measurements on single trapped Yb^+ and Sr^+ ion clocks

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We present recent phonon heating rates for a new single-ion end-cap trap design [1] with optimised choice of materials and geometry to minimise ion–environment interactions. A single $^{171}\text{Yb}^+$ ion confined within the trap exhibits an anomalous phonon heating rate of $dn/dt = 24(+30 - 24)\text{s}^{-1}$. The thermal properties of the trap structure have also been measured, giving an effective temperature rise at the ion's position of $T(\text{ion}) = 0.14 \pm 0.14\text{K}$. These small perturbations to the ion caused by this trap demonstrate its suitability for an optical frequency standard achieving fractional uncertainties below the 10^{-18} level.

For ions trapped in well-controlled thermal environments, knowledge of the blackbody radiation (BBR) shift is limited by uncertainty in the atomic polarisability coefficient rather than by temperature uncertainty. We therefore measure the atomic polarisabilities for the octupole (E3) and quadrupole (E2) optical clock transitions in $^{171}\text{Yb}^+$. The experiments were carried out using a mid-infrared laser frequency to provide an AC Stark field in the wavelength region characteristic of room-temperature blackbody ra-

diation. The results lead to a several-fold reduction in the achievable BBR fractional frequency shift uncertainty for the E2 clock transition, and the BBR shift for the E3 clock transition agrees well with an independent measurement. Additionally, we also discuss scalar AC Stark shift measurements on the single $^{88}\text{Sr}^+$ ion clock at 1064 nm in order to determine the blackbody shift for this ion clock system.

We also present an absolute frequency measurement of the $2S_{1/2} - 2F_{7/2}$ octupole clock frequency, by means of a frequency link to International Atomic Time to provide traceability to the SI second [2]. The $^{171}\text{Yb}^+$ optical frequency standard was operated with an up-time of 76% over a 25-day period, with the absolute frequency measured to be 642 121 496 772 645.14(26) Hz. The fractional uncertainty of 4×10^{-16} is comparable to that of the best previously reported measurement, which was made by a direct comparison to local caesium primary frequency standards [2].

This work is supported by the UK Department for Business, Energy and Industrial Strategy as part of the National Measurement System Programme, and also the European Metrology Research Programme (EMRP) project SIB55-ITOC and the European Metrology Programme for Innovation and Research (EMPIR) project 15SIB03-OC18.

- [1] P. B. R. Nisbet-Jones, S. A. King, J. M. Jones, R. M. Godun, C. F. A. Baynham, K. Bongs, M. Doležal, P. Balling, P. Gill, *Appl. Phys. B* **122** 57 (2016)
- [2] C. F. A. Baynham, R. M. Godun, J. M. Jones, S. A. King, P. B. R. Nisbet-Jones, F. Baynes, A. Rolland, P. E. G. Baird, K. Bongs, P. Gill and H. S. Margolis <http://arxiv.org/abs/1707.00646>
- [3] N. Huntemann, B. Lipphardt, Chr. Tamm, V. Gerginov, S. Weyers, E. Peik. *Phys. Rev. Lett.* **113**, 210802 (2014)

Thursday, August 17, 1200-1230

Reducing time dilation uncertainty in the NIST Al⁺ optical clocks

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The $^1S_0 \leftrightarrow ^3P_0$ transition in $^{27}\text{Al}^+$ is used as a frequency reference in several optical clocks around the world due to its narrow natural linewidth ($\delta\nu \sim 8$ mHz) and relative insensitivity to perturbation from external electromagnetic fields. Spectroscopy can be performed, without direct laser cooling or detection, by use of a second ion for sympathetic cooling and state detection, based on quantum logic [1]. Previous experiments have demonstrated fractional uncertainty of these frequency standards below the level of 1×10^{-17} for both statistical and systematic errors [2]. A primary limitation to clock accuracy has been ion motion, which causes frequency shifts due to time dilation. In this talk, I will describe recent results from the Al⁺ clock experiments at NIST, where we reduced secular motion time-dilation shifts to $(-1.9 \pm 0.1) \times 10^{-18}$ by cooling the ions to near the three-dimensional ground state of motion [4]. Likewise, by minimizing and characterizing excess micromotion in a new trap, we have reduced

the micromotion time dilation shift to near 5×10^{-18} , with the uncertainty currently under evaluation. Clock stability has been primarily limited by quantum projection noise. We plan to improve this by increasing the stability of the probe laser and by implementing new clock comparison protocols that suppress the effects of correlated laser noise in clocks probed by phase-locked laser sources [3, 5]. This work was supported by the Office of Naval Research and the Defense Advanced Research Projects Agency. S.M.B. was supported by ARO through MURI grant W911NF-11-1-0400.

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- [2] C. W. Chou *et al.*, *Phys. Rev. Lett.* **104** 070802 (2010)
- [3] C. W. Chou *et al.*, *Phys. Rev. Lett.* **106** 160801 (2011)
- [4] J. S. Chen *et al.*, *Phys. Rev. Lett.* **118** 053002 (2017)
- [5] D. B. Hume and D. R. Leibbrandt, *Phys. Rev. A* **93** 032138 (2016)

Thursday, August 17, 1400-1430

Sequential quantum measurements on trapped ions

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I will describe experiments in which sequences of idealized quantum measurements are performed on trapped ion systems spanning a Hilbert space of more than one qubit. Using the internal states of a mixed-species ion chain containing beryllium qubits and a calcium ancilla, we have performed up to 50 sequential parity measurements, which combined with real-time feedback allows stabilization of the multi-qubit system. In the oscillator degree of freedom, we have realized modular variable measurements, demonstrating violation of a Leggett-Garg inequality and the use of the oscillator for an encoded qubit relevant for quantum error-correction with continuous variable states. Finally, using a qutrit stored in a calcium ion, we have demonstrated the sustained generation of contextual correlations over 53 million measurements [2].

- [1] D. Gottesman, J. Preskill and A. Kitaev, Phys. Rev. A 64, 012310 (2001)
- [2] F. Leupold *et al.*, arXiv:1706.07370 (2017)

Thursday, August 17, 1430-1500

High-fidelity qubit operations in microfabricated surface ion traps

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Microfabricated surface ion traps enable scaling of trapped ion quantum information systems from single ion chains to large traps with multiple dedicated trapping zones [1]. The flexibility provided by moving ions between trapping zones and thus rearranging qubits in a quantum processor combined with the full connectivity of operations within a single ion chain are strengths of the trapped ion platform for quantum information processing.

With Sandia's High Optical Access (HOA) surface traps, we demonstrate classical shuttling operations including local reordering of ions through ion-crystal rotations, separation and merging of ion crystals, and transport of ions through linear sections and junctions. We use Gate Set Tomography (GST) to optimize the implemented quantum gates, minimize model violations, and demonstrate single-qubit gates above a proven fault-tolerance threshold against general noise [2] by demonstrating a diamond norm distance below $8(1) \times 10^{-5}$ [3]. Furthermore, we realize a Mølmer-Sørensen two-qubit gate and analyze the quantum process with GST, achieving a process infidelity below 0.5%. These

results demonstrate the viability of microfabricated surface traps for the use in state of the art quantum information processing systems.

[†]Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

- [1] D. Kielpinski, C. Monroe, and D. J. Wineland. *Nature*, 417(6890):709, June 2002.
- [2] P. Aliferis and J. Preskill, *Phys. Rev. A* **79**, 012332 (2009).
- [3] R. Blume-Kohout *et al.*, *Nature Communications* **8**, 14485 (2017).

Thursday, August 17, 1500-1530

Joint quantum state and measurement tomography with incomplete measurements

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Estimation of quantum state preparations and measurements is crucial for the implementation of quantum information protocols. The standard method for each is quantum tomography (QT). However, QT suffers from systematic errors caused by imperfect knowledge of the system. We present an algorithm to simultaneously characterize quantum states and measurements that mitigates systematic errors by use of a single high-fidelity state preparation and a limited set of high-fidelity unitary operations. Such states and operations are typical of many state-of-the-art systems. We construct a set of experiments for the situation in question and use alternating maximum likelihood iterations to estimate measurement operators and other quantum states. In some cases, the protocol does not enable unique estimation of the state. For these cases, we show one may identify a set of density matrices compatible with the measurements and use a semi-definite program to place bounds on the

state's expectation values. We apply these methods to a simulation of two trapped ions to demonstrate the protocol.

Thursday, August 17, 1600-1630

Quantum signal processing for trapped ion qubit metrology

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Trapped ion qubits can be exquisite sensors of forces and fields, and their long coherence times admit a wide range of quantum protocols for amplifying the sensed signal in ways which exceed classical metrology limits. Building on our theoretical proposal for Heisenberg-limited imaging using coherent enhancement[1], and a methodology we have presented for constructing composite quantum gates to sculpt desired single-qubit response functions[2], we present a “quantum signal processing” framework for manipulating signals sensed by a single qubit. This framework saturates performance bounds on resources required for quantum Hamiltonian simulation[3], and also opens doors for new approaches to quantum-limited metrology with trapped ions.

- [1] *Quantum Imaging by Coherent Enhancement*, Guang Hao Low, Theodore J. Yoder, and Isaac L. Chuang, Phys. Rev. Lett. **114**, 100801 (2015)
- [2] *Methodology of Resonant Equiangular Composite Quantum Gates*, Guang Hao Low, Theodore J. Yoder, and Isaac L. Chuang, Phys. Rev. X **6**, 041067 (2016)

- [3] *Optimal Hamiltonian Simulation by Quantum Signal Processing*, Guang Hao Low and Isaac L. Chuang, Phys. Rev. Lett. **118**, 010501 (2017)

Thursday, August 17, 1630-1700

Amplitude sensing below the zero-point fluctuations with a two-dimensional trapped-ion mechanical oscillator

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We present a technique to measure the amplitude of a center-of-mass (COM) motion of a two-dimensional ion crystal composed of ~ 100 ions in a Penning trap [1]. The technique employs a spin-dependent, optical-dipole force to couple the mechanical oscillation to the frequency of the valence electron spin-flip transition of the trapped ions. An amplitude-dependent spin precession occurs, enabling a measurement of one quadrature of the COM motion through a readout of the spin state.

Laser-cooled trapped ions are sensitive detectors of weak forces and electric fields. Prior work with single ions and large ion arrays has produced impressive sensitivities using Doppler velocimetry [2, 3] and injection-locking techniques [4]. Single ions have been used to investigate heating rates produced by weak stochastic fields [5] by mapping the excited motion to the spin-state. A single measurement with a single ion provides a measurement with a signal-to-noise of ~ 1 . Large ion numbers enable a given amplitude of COM motion to be measured with high signal-to-noise because of

reduced projection noise.

With this work, we exploit our large array of ions and measure ion-displacement-induced spin dephasing. By sensing motion at frequencies far from the COM resonance frequency, we experimentally determine the technique's measurement imprecision. We resolve amplitudes as small as 50 pm, 40 times smaller than the COM mode zero-point fluctuations. We demonstrate sensitivity limits set by spin projection noise and spin decoherence due to off-resonant light scattering. When performed on resonance with the COM mode frequency, the technique demonstrated here can enable the detection of extremely weak forces (< 1 yN) and electric fields (< 1 nV/m), providing an opportunity to probe quantum sensing limits and search for dark matter candidates such as hidden photons.

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- [2] M. J. Biercuk *et al.*, Nat. Nanotechnol. **5**, 646 (2010)
- [3] R. Shaniv *et al.*, Nat. Commun. **8**, 14157 (2017)
- [4] S. Knünz *et al.*, Phys. Rev. Lett. **105**, 013004 (2010)
- [5] R. Maiwald *et al.*, Nat. Phys. **5**, 551 (2009)

Friday, August 18, 0900-0930

Optical sideband cooling of ions in a Penning trap

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We have previously demonstrated optical sideband cooling of the axial motion of a single ion in a Penning ion trap [1]. Due to the low oscillation frequencies available in a Penning trap, the cooling starts from well outside the Lamb-Dicke regime. This means that it is not sufficient to cool using the first red motional sideband, since after Doppler cooling there is a significant part of the population in Fock states that are above the first zero of this sideband. A sequence of pulses tuned to different motional sidebands is required to reach the ground state of the motion.

For a two-ion axial crystal, this problem gets worse as the trapping voltage has to be reduced (otherwise the axial crystal is not stable). Furthermore, the interaction of the two vibrational modes with each other leads to more possibilities for the trapping of parts of the population in high-lying Fock states. We have developed complex pulse sequences to overcome these problems and have successfully cooled two-ion crystals to the ground state of both axial modes simultaneously [2]. We have also achieved this for the axial motion of

a two-ion radial crystal, where the two modes are close to degenerate, which considerably simplifies the process.

We will present our cooling results, together with computer simulations of the cooling process. We demonstrate long motional coherence times (of the order of 1 second) and low heating rates in our trap. By driving a single ion on the first blue sideband in a "sideband heating" process, we can prepare the ion in a narrow range of Fock states around the first minimum of this sideband (where $n \sim 100$). We still observe long motional coherence times, even for these high- n Fock states.

We will also present our latest results for sideband cooling of the cyclotron and magnetron radial motions of a single ion in a Penning trap. We achieved this using the axialisation technique, which is closely related to the rotating wall technique used in other experiments. We achieve $\bar{n} < 1$ for both radial modes simultaneously.

- [1] Joseph F. Goodwin et al., *Physical Review Letters*, 116(14):143002 (2016).
- [2] Graham Stutter et al., *arXiv:1705.08518v1* (2017).

Friday, August 18, 0930-1000

Scaling to larger mixed species ion trap quantum computers; measurements of sympathetic cooling and normal mode coupling in trapped Ba-Yb chains

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The use of mixed species in trapped ion chains facilitates non-destructive remote entanglement and sympathetic cooling. For either of these techniques to be useful for quantum computation, motional coupling between the different ion species must be sufficiently strong. $^{138}\text{Ba}^+$ and $^{171}\text{Yb}^+$ are both good qubit candidates with useful properties for quantum computation, but their 25% mass difference is large enough to cause motional decoupling under naive conditions. In this talk I will discuss per-vibrational mode energy measurements of sympathetically cooled mixed species chains of Barium and Ytterbium, and those measurements' agreement with numerical calculations of the normal mode couplings. I will also discuss necessary parameters for scaling to larger chains while ensuring strong coupling along with supporting numerical analysis.

Friday, August 18, 1000-1030

Laser-cooling and trapping the Goldilocks qubit: ¹³³Ba⁺

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Atomic ions can be isolated from their environment through laser-cooling and trapping, making them useful for quantum information processing and precision measurement. Qubits, defined by pairs of long-lived states where quantum superpositions can be maintained, are prepared, manipulated, and interrogated with electromagnetic fields. A variety of atomic ion species have been used as qubits. Hyperfine qubits with nuclear spin $I = 1/2$ have demonstrated the longest qubit coherence times with simple, robust laser manipulation of the trapped ion qubit. Other hyperfine qubits ($I \neq 1/2$) have easily-prepared, long-lived metastable electronic excited states, and simple discrimination between these states and the electronic ground states results in the highest fidelity readout of a trapped ion qubit. However, none of the naturally-occurring, atomic ions with nuclear spin $I = 1/2$ have these excited states that are simultaneously long-lived and easy to prepare. In addition, the optical transitions of the naturally-occurring spin $I = 1/2$ nuclei are in the ultra violet, where appreciable laser power is difficult to obtain. We demonstrate loading and cooling of an

artificial, $I = 1/2$ species of barium with visible wavelength lasers: $^{133}\text{Ba}^+$. Using a single trapped atom of $^{133}\text{Ba}^+$, we measured the isotope shifts and hyperfine structure of the laser-cooling transitions near 493 nm and 650 nm [1]. An efficient loading technique was used to trap this radioisotope without requiring hazardous amounts of source material. This ion has nuclear spin $I = 1/2$, easily-prepared and long-lived metastable excited states, and utilizes visible wavelengths for laser cooling. $^{133}\text{Ba}^+$ offers the tantalizing possibility of being the optimal trapped atomic ion qubit as it simultaneously combines the advantages of many different ion qubits into a single system.

[1] D. Hucul *et al.*, arXiv:1705.09736 (2017)

Friday, August 18, 1100-1130

Coherent internal state manipulation of single atomic and molecular ions by optical frequency combs

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Coherent manipulation of state-prepared molecular ions are of interest for a wide range of research fields, including ultra-cold chemistry, ultra-high resolution spectroscopy for test of fundamental physics, and quantum information science. Recently, there has been significant advances with respect to both preparing trapped molecular ions in their quantized motional ground state [1, 2, 3], and controlling their rovibrational degrees of freedom through a series of different techniques [4, 5, 6, 7, 8, 9, 10, 11]. This talk will focus on coherent manipulation of the internal states of single atomic and molecular ions through the exposure of such ions to optical frequency comb (OFC) [12, 13, 14]. Based on recent coherent manipulations of the population between the metastable $3d\ ^2D_{3/2}$ and $3d\ ^2D_{5/2}$ levels in the Ca^+ ion separated by 1.8 THz, we will discuss next experiments on coherent rotational state manipulation of the MgH^+ ion, as well as comment on the perspective of using this manipulation technique in connection coherently controlled reaction experiments.

- [1] G. Poulsen, PhD thesis: *Sideband Cooling of Atomic and Molecular Ions*,
Department of Physics and Astronomy, Aarhus University, 2011.
- [2] Y. Wan *et al.*, Phys. Rev. A 043425, **91** (2015)
- [3] R. Rugango *et al.*, New J. Phys. 03009, **17** (2015)
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- [8] A. K. Hansen *et al.*, Nature 76, (**508** (2014)
- [9] C.-Y. Lien *et al.*, Nat. Comm. 4783, (**5** (2014)
- [10] F. Wolf *et al.*, Nature 457, (**530** (2016)
- [11] C.-W. Chou *et al.*, Nature 203, (**545** (2017)
- [12] D. Hayes *et al.*, Phys. Rev. Lett. 140501, **104** (2010)
- [13] S. Ding and D. N. Matsukevich, New J. Phys. 023028, **12** (2012)
- [14] D. Leibfried, New J. Phys. 023029, **12** (2012)

Friday, August 18, 1130-1200

Quantum state preparation and detection of a single molecular ion using a quasi-cycling transition

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Spectroscopy of rovibrational transitions in molecules is uniquely capable of providing tighter limits on the variation of the proton-to-electron mass ratio. Record breaking limits can be set by taking advantage of the remarkable environmental isolation available to single molecular ion experiments. The lack of cycling transitions in molecules however, still poses a formidable challenge for quantum state preparation and detection. While successful state detection for molecular ions has been demonstrated by adapting quantum logic spectroscopy, slow state preparation times currently limit molecular experiments from reaching the statistical sensitivity achieved with atomic ions.

In this talk I will discuss our use of molecules having quasi-cycling transitions, which supply a photon scattering budget sufficiently large enough to implement fast, optical state preparation and detection techniques. Using such transitions, we will prepare a single molecular ion in its rotational ground state using a spectrally shaped broadband laser as we demonstrated previously [1]. I will describe our plan to use a quasi-cycling transition to implement photon recoil read-

out, a relatively simple nondestructive state readout scheme using a broadband laser. In addition to our current progress toward preparing and detecting a single molecular ion [2], I will discuss our approach for ultimately achieving rovibrational spectroscopy using the culmination of these techniques. Lastly, I will conclude with our efforts toward finding new molecules with both quasi-cycling transitions and higher sensitivities to a variation of the proton-to-electron mass ratio.

[1] C. Y. Lien *et al.*, Nat. Commun. **5**, 4783 (2014)

[2] C. M. Seck *et al.*, Phys. Rev. A **93**, 053415 (2016)

Friday, August 18, 1200-1230

Quantum chemistry and non-equilibrium thermodynamics in an atom-ion hybrid trap

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Hybrid atom-ion traps allow for the precise control and investigation of atom-ion collisions in the ultracold regime. While these systems have previously been utilized for the production of ground state molecular ions via sympathetic cold atom collisions[1], recently our group has utilized these platforms for the study of quantum chemistry and non-equilibrium thermodynamics.

In this presentation we describe work conducted with the MOTion trap - a hybrid atom-ion trap consisting of a linear quadrupole ion trap (LQT) and a co-located magneto-optical trap (MOT). With the long interrogation times associated with the ion trap environment and precisely tunable entrance channels of both the atom and ion via laser excitation, the MOTion trap is a convenient platform for the study of quantum state resolvable cold chemistry. We describe a recent study of excited state chemistry between cold Ca atoms and the BaOCH_3^+ molecular ion, which has resulted in the product BaOCa^+ , the first observed mixed hypermetallic alkaline earth oxide molecule.

Further, due to the complexity of ion-ion heating within an LQT and micromotion interruption collisions, there remain many open questions about the thermodynamics of ions in a hybrid trap environment. We describe an analytical model that explains the thermodynamics of these systems as well as an experimental effort confirming one of the more interesting hallmarks of this model, the bifurcation in steady state energy of ions immersed in an ultracold gas, as parameterized by total ion number[2].

Finally, we also present the identification of improved repumping schemes for the Ca laser cooling cycle, which has resulted in order of magnitude enhancements in both Ca MOT lifetime and atom number density. While of particular interest to groups utilizing Ca MOT's, this work may also be helpful in identifying similarly useful repump transitions in other alkaline earth atoms.

[1] W. Rellergert *et al.*, *Nature*. **495**, (2013)

[2] S. Schowalter *et al.*, *Nat. Commun.* **7**, (2016)

Friday, August 18, 1400-1430

Measuring and modeling noisy gates

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Fault tolerance threshold proofs assume that errors in quantum circuits are uncorrelated. Recently at GTRI, we have used spectroscopic techniques to identify sources of noise affecting our trapped ion chain [1]. We have observed that many controls exhibit correlated noise, but our models of how this noise affects the resulting gate error are incomplete. To improve modeling and understand our errors in a fault tolerant context, GTRI has developed hardware for injecting noise on various control parameters. I will present recent results in which our models are in quantitative agreement with noisy experiments on a single ion. Progress towards testing the effect of noise with small circuits of gates will also be discussed.

[1] S. D. Fallek *et al.*, New J. Phys. **18**, 083030 (2016)

Friday, August 18, 1430-1500

Microwave-driven quantum logic with trapped ions

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Fidelities approaching the level required for large-scale QIP have been demonstrated in experiments with small numbers of qubits. However, scaling these proof-of-principle experiments to larger numbers of qubits presents a significant challenge. One promising route for overcoming this challenge is replacing the laser systems traditionally used to drive logic operations on trapped-ion qubits with microwave electronics integrated into microfabricated ion traps [1][2][3]. In the long term, this technique may also allow higher operation fidelities than laser-based gates due to the absence of photon scattering from excited states.

I present recent work at Oxford on microwave-driven trapped-ion quantum logic, including a two-qubit gate using a novel dynamically-decoupled gate mechanism, with which we achieved 99.7% fidelity [4]. I describe the major experimental challenges faced by microwave quantum logic, the progress we have made towards overcoming them, and our plans for a next-generation apparatus featuring cryogenic cooling and a more advanced trap design.

[1] F. Mintert and C. Wunderlich, Phys. Rev. Lett. **87** 257904 (2001)

[2] C. Ospelkaus *et al.*, Phys. Rev. Lett. **101** 090502 (2008)

- [3] C. Ospelkaus *et al.*, *Nature* **476** 181 (2011)
- [4] T. P. Harty *et al.*, *Phys. Rev. Lett.* **117** 140501 (2016)

Friday, August 18, 1500-1530

Trapped-ion quantum logic with near-field microwave-driven gates

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Hyperfine qubits in laser-cooled trapped atomic ions are one of the most promising platforms for general-purpose quantum computing. Magnetic field-insensitive ‘clock states’ and near-infinite lifetimes allow for minute-long memory coherence times as well as qubit frequencies that are in the convenient microwave domain [1]. Most work on these qubits has so far focussed on using lasers for gate operations, however there are several schemes that offer the prospect of performing all coherent operations using purely electronic methods [2, 2]. This replaces lasers with cheaper, smaller, more stable microwave devices with more straightforward phase control. Microwave elements can also be integrated into trapping structures more easily than their optical counterparts for improved scalability. The latest results using near-field microwaves have demonstrated two-qubit gate fidelities of 99.7(1)% [3], as well as single-qubit state preparation, gates, memory and read-out fidelities exceeding 99.9% [1]. I will present the latest results on a new ion trap system being developed to exceed these fidelities whilst incorporating new functional elements. Foremost amongst these will be

the addition of an auxiliary ion species and a multi-zone trap to enable arbitrary multi-qubit operations [5]. The important experimental techniques of cryogenic cooling and in-situ surface cleaning have also been incorporated.

Supported by IARPA and the NIST quantum information program

- [1] T. P. Harty *et al.* Phys. Rev. Lett. **113**, 220501 (2014)
- [2] C. Ospelkaus *et al.* Phys. Rev. Lett. **101**, 090502 (2008)
- [3] F. Mintert, and C. Wunderlich, Phys. Rev. Lett. **87**, 257904 (2001)
- [4] T. P. Harty *et al.* Phys. Rev. Lett. **117**, 140501 (2016)
- [5] D. J. Wineland *et al.* J. Res. Natl. Technol. **103**, 259 (1998).

List of posters

Odd-numbered posters: Poster session 1, Mon. Aug 14, 4 pm

Even-numbered posters: Poster session 2, Wed. Aug 16, 4 pm

Posters (alphabetically by presenting author)

Poster No.	Name	Title
1	Yuhi Aikyo	Stabilization of a 493 nm laser frequency by a polarization spectroscopy for a multi-species ion trap system
2	Nitzan Akerman	Kinetics, electronic and spin dynamics in ultracold ion-atom collisions
3	Kristin M. Beck	Boson dynamics with normal and local modes in a linear ion chain
4	Ivan A. Boldin	Measuring anomalous heating in a planar ion trap with variable ion-surface separation
5	Samuel M. Brewer	Systematic uncertainty evaluation of an $^{27}\text{Al}^+$ quantum-logic clock
6	Joe W. Britton	Progress towards cavity mediated ion photon coupling
7	Colin D. Bruzewicz	Visible-wavelength mixed-species quantum logic
8	Shaun C. Burd	Optically pumped semiconductor lasers for atomic physics
9	Aaron T. Calvin	Spectroscopy on sympathetically cooled CaH^+

10	Vincent Carrat	Optically resettable state manipulation of a molecular ion
11	Justin E. Christensen	$^{133}\text{Ba}^+$: A synthetic trapped ion qubit
12	Ethan R. Clements	Advances in RF Paul traps and vacuum systems for ion clocks
13	Govinda Clos	Time-resolved observation of thermalization in an isolated quantum system
14	Stephen Crain	System characterization of a trapped ion based quantum computer
15	Jin-Ming Cui	Experimentally detecting the resource of fault-tolerant quantum computation by state-dependent contextuality
16	Swarup Das	A simple magnetometer with single trapped ion
17	Marion Delehaye	Characterization of the phase-noise induced by an optical frequency doubler
18	Ke Deng	Progress report on $^{25}\text{Mg}^+$ trapping and cooling for a $^{25}\text{Mg}^+ - ^{27}\text{Al}^+$ quantum logic optical clock
19	Petr Dohnal	Reactions of Ar^+ and ArH^+ ions with normal and para-enriched H_2
20	Joan M. Dreiling	Capture of highly charged ions in a hyperbolic Paul trap
21	Pascal Eich	Entanglement transfer via a programmable ion-photon interface
22	Stephen Erickson	Chained Bell inequality experiment with high-efficiency measurements
23	Spencer D. Fallek	Improving stability and modeling noise in ion experiments

24	Chao Fang	MEMS-based beam steering for scalable quantum gate operations with trapped ion qubits
25	Christoph Fischer	Trapping ions in an optical lattice for quantum simulation
26	Henning Furst	Observation of cold collisions between Li and Yb ⁺
27	Lukas Gerster	Scalable quantum computation - keeping a qubit alive
28	Kevin A. Gilmore	Measuring entanglement and many-body correlations with a hundred-ion quantum simulator
29	James Greenberg	Quantum state controlled, radical-ion reactions
30	Luca Guidoni	Sympathetic cooling of ⁹ Be ⁺ by ⁸⁸ Sr ⁺ Doppler cooled ions in large Coulomb crystals: an experimental study
31	Roland Hablutzel	Applications of the trilinear Hamiltonian with three trapped ions
32	John Hannegan	Towards telecom photons entangled with Ba ⁺
33	Oded Heber	A novel ion cooling process using autoresonance in an electrostatic ion beam trap
34	Seokjun Hong	Investigation of charging effects of exposed dielectric surfaces in surface ion-trap chips
35	Yun-Feng Huang	Nondegenerate elliptical fiber Fabry-Perot cavities with large tunable splitting

36	Kai M. Hudek	An error-corrected, universal, re-configurable, ion-trap quantum archetype
37	Elena Jordan	Toward ground state cooling of hundreds of ions in a Penning trap
38	Masatoshi Kajita	Attainable accuracy of vibrational transition frequencies of homonuclear diatomic molecular ions
39	Grzegorz Kasprawicz	Sinara: open source modular hardware for quantum physics
40	Jonas Keller	Toward quantum simulations with ions in 2D microtrap arrays
41	Philip Kiefer	Spectroscopy and transport of topological solitons in Coulomb crystals
42	Kilian W. Kluge	Quantum networks with single trapped ions in fiber cavities
43	Christoph Kurz	Preparation and coherent manipulation of pure quantum states of a single molecular ion
44	Kirill Lakhmanskiy	Ion motional heating rate on a high-temperature superconducting YBCO surface trap
45	Jennifer F. Lilieholm	Single ion imaging and fluorescence collection with a parabolic mirror trap
46	Zhenyu Liu	Quantum simulation of the quantum Rabi model in a single trapped ion
47	Daniel Lobser	Quantum and classical control of ions in Sandia's HOA trap
48	Yao Lu	Verification of quantum non-equilibrium work and fluctuation relations in the presence of decoherence

49	Yao Lu	Quantum simulation of molecular spectroscopy with trapped ion
50	Le Luo	Fabrication of ion-trap electrodes by self-terminated electrochemical etching
51	Roland Matt	Scalable cryogenic experiment for trapped-ion quantum computing
52	Karl Mayer	Bounding the quantum process fidelity with a minimal set of input states
53	Robert P. McConnell	Integrated technologies for chip-scale trapped-ion quantum control
54	Katherine C. McCormick	Towards a 2-D trapped-ion quantum simulator
55	Mikhail Miller	State controlled ion-neutral reactions
56	Steven Moses	Two-qubit entanglement with ultrafast laser pulses
57	Aung Sis Naing	Testing a dual-anode miniature electron beam ion trap for the production of highly charged ions
58	Vlad Negnevitsky	Repeated multi-qubit parity measurement, feedback and stabilization using a mixed-species ion crystal
59	Thanh Long Nguyen	Preparation of Grid state qubits by sequential modular position measurements of trapped ions motion
60	Nozomi Ohtsubo	Frequency measurement of the clock transition of In^+ ion sympathetically-cooled with Ca^+ ions
61	Christian Ospelkaus	Towards quantum logic inspired cooling and detection for single (anti-)protons

62	Mikel Palmero	Shortcuts to adiabaticity for fast operations with trapped ions
63	David Patterson	A path to polyatomic molecular ions in single quantum states
64	Jussi-Pekka Penttinen	VECSEL – a versatile laser tool for ion trappers
65	Melissa C. Revelle	Microfabricated microwave-integrated surface ion trap
66	Štěpán Roučka	Experimental study of endothermic isotope exchange at low temperatures
67	Brian Sawyer	A compact Penning trap frequency reference
68	Vera M. Schäfer	Fast entangling gates with trapped ions
69	Philipp Schmid	Isomer-selective organic chemistry between cations and neutrals under controlled conditions
70	George Y. Schwartz	Micromirror fabrication and characterization for cavity-QED with trapped ions
71	Ravid Shaniv	Heisenberg-limited Rabi spectroscopy
72	Daniel H. Slichter	Superconducting photon detectors for integration in an ion trap
73	Robert E. Spivey	Characterization of a compact cryogenic package approach to ion trap quantum computing
74	Raghavendra Srinivas	Progress towards high-fidelity microwave two-qubit gates with trapped ions
75	Erik W. Streed	A single-atom 3D sub-attoneutron force sensor

76	James E. Tarlton	Qubit decoherence metrology over short timescales
77	Keshav Thirumalai	Development of a photonicallly linked ion trap network
78	Susanna L. Todaro	A new closed cycle cryostat system for quantum information experiments with trapped ions
79	Yong Wan	Complete set of transport primitives for scalable quantum computing using trapped ions
80	Pengfei Wang	The exponential gain of randomness certified by quantum contextuality
81	Ye Wang	Single-qubit quantum memory exceeding 10-minute coherence time
82	Simon C. Webster	Constructing a microwave trapped ion quantum computer
83	Laura Wessing	Quantum networking with trapped-ion qubits at AFRL
84	Adam D. West	Rotation sensing with trapped ions
85	Guido Wilpers	Parallel MEMS fabrication and operation of 3D ion traps
86	Guido Wilpers	Towards reduced motional decoherence in ion microtraps
87	Fabian Wolf	Quantum sensing of oscillating forces without phase control
88	Jochen Wolf	Quantum logic gates driven by near-field microwaves
89	Chi Zhang	Motional state squeezing and contextuality tests with qutrits on a cryogenic surface-electrode trap

90	Junhua Zhang	Experimental preparation of high NOON states for phonons
91	Junhua Zhang	Multi-species trapped ion system with $^{171}\text{Yb}^+$ and $^{138}\text{Ba}^+$
92	Liudmila Zhukas	Measuring the temperature of barium and ytterbium in mixed species linear chains
93	Mang Feng	Verifying Heisenberg's error-disturbance relation using a single trapped ion
94	Xue-ren Huang	Sympathetic sideband cooling of a $^{40}\text{Ca}^+ - ^{27}\text{Al}^+$ pair towards quantum logic clock

Poster abstracts

Poster No. 1

Stabilization of a 493 nm laser frequency by a polarization spectroscopy for a multi-species ion trap system

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We demonstrate frequency stabilization of an external cavity diode laser at 493 nm via polarization spectroscopy for use in the cooling of trapped Ba⁺ ions. Our schema is Doppler free and employs a hollow cathode lamp which provides a plasma of Ba⁺ ions. A pump beam induces a birefringence in the plasma which is detected by observing the polarization dependent response of a probe beam on a balanced photodetector. The resultant error signal is used to stabilize the laser to less than 1 MHz at the measured 493.545 nm line of Ba⁺138.

Poster No. 2

Kinetics, electronic and spin dynamics in ultracold ion-atom collisions

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We have studied the dynamics of a ground-state cooled single Sr^+ ion during collisions with ultra-cold Rb atoms. Even in the absence of excess micromotion we find that the ion heats up and acquires a non-equilibrium energy distribution with a power-law tail[1]. In a different experiment we measured the spin dynamics of the ion. We show that when the atomic ensemble is polarized, spin-exchange collisions polarized the spin of the ion. Finally we studied the dynamics of a single ion when it is optically excited into a meta-stable D level. Here we see that the ion and atoms non-adiabatically exchange the electronic excitation where the excess energy is released into the kinetic motion of the ion and atom. By applying new thermometry methods to the ion motion we are able to identify the various processes.

[1] Z. Meir *et al.*, Phys. Rev. Lett. **117**,243401 (2016)

Poster No. 3**Boson dynamics with normal and local modes in a linear ion chain**

K. Beck¹, K. Wright^{1,2}, D. Zhu¹, K. Collins¹, S. Debnath^{1,3}, C. Figgatt¹,
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We report two experiments that manipulate phonons on a linear chain of three Yb^+ ions for quantum simulation. In the first, we have developed a toolbox for creating, manipulating, and reading out phonon states in the normal modes of motion of such a chain on a surface electrode trap. We combine shuttling, composite pulse sequences, and state distillation to prepare phonon number states, and use STIRAP pulses to measure the resulting phonon number distribution. In a separate project, we observe phonon hopping between local motional modes in a loosely bound chain in a blade trap. We introduce local "phonon blockades" on targeted sites to inhibit hopping by individually addressing an ion and coupling the internal spin state with its local phonon mode.

Measuring anomalous heating in a planar ion trap with variable ion-surface separation

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Electric field noise in the vicinity of metal surfaces is an important issue in various fields of experimental physics. In experiments with cold trapped ions such noise results in heating of the ions' motional degrees of freedom. In realizations of quantum information processing based on trapped ions this heating can become a major source of decoherence. The rate of this heating is orders of magnitude larger than expected from electric field fluctuations due to thermal motion of electrons in the conductors. This effect is known as anomalous heating, and its mechanism is not fully understood. One of the open questions is the heating rate dependence on the ion-electrode separation. We present a first time direct measurement of this dependence in an ion trap of planar geometry. The heating rates are determined by taking images of ions after heating and measuring the average oscillation amplitude. Assuming a power law for the heating rate vs ion-surface separation dependence, an exponent of -3.79 ± 0.12 has been measured.

Poster No. 5**Systematic uncertainty evaluation of an $^{27}\text{Al}^+$ quantum-logic clock**

S. M. Brewer¹, J. S. Chen^{1,2}, A. M. Hankin¹, E. R. Clements^{1,2}, C. W. Chou¹, D. J. Wineland^{1,2}, D. R. Leibbrandt^{1,2}, and D. B. Hume¹

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Previous optical atomic clocks based on quantum-logic spectroscopy of the $^1S_0 \longleftrightarrow ^3P_0$ transition of $^{27}\text{Al}^+$ reached an uncertainty of $\delta \nu / \nu < 1 \times 10^{-17}$. This uncertainty was dominated by environmental effects related to the traps used to confine the ions; i.e. time-dilation shifts due to motion of the ions in the trap and the blackbody radiation (BBR) shift due to elevated trap temperature. Improvements in a new trap have reduced excess micromotion and secular heating, making it possible to operate the clock near the three-dimensional motional ground state, and leading to a reduced time-dilation shift uncertainty. In addition, the operating temperature of the system has been lowered to reduce the BBR shift uncertainty. Here we present the systematic uncertainty evaluation of a new $^{27}\text{Al}^+$ quantum-logic clock based on this improved trap design. This work was supported by ONR and DARPA. S.M.B. was supported by ARO through MURI grant W911NF-11-1-0400.

Poster No. 6

Progress towards cavity mediated ion photon coupling

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Entanglement is a resource that enables quantum-coherent communication, distributed sensing and scaling of quantum computers. A modular network of ion traps is one platform amenable to entanglement distribution. This poster reports on progress toward setting up an HOA-2 ion trap for 171Yb^+ ions serving as a quantum memory and exploration of ion-photon coupling mediated by high finesse optical cavities.

Poster No. 7

Visible-wavelength mixed-species quantum logic

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Motional heating and photon-scattering-induced decoherence are major obstacles to the development of large-scale, trapped-ion quantum processors. Both effects can be mitigated via a second, auxiliary ion species that can serve as a sympathetic coolant and as an accurate proxy during quantum state detection. In a mixed-species ion chain, we transfer the quantum state of a memory ion ($^{40}\text{Ca}^+$) to an auxiliary ion ($^{88}\text{Sr}^+$) using their shared motion as a quantum bus. We then read out the state of the auxiliary ion and demonstrate an overall transfer and measurement efficiency of 96(1)%. This technique can significantly reduce decoherence due to resonant photon scatter in other nearby unmeasured memory ions. Additionally, the ion species used here utilize lasers in the visible and near-infrared portion of the spectrum. Hence, the necessary beams can be routed using low-loss integrated waveguides, rather than free-space optics, in future scalable trap designs.

Poster No. 8**Optically pumped semiconductor lasers for atomic physics**

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Experiments in atomic, molecular, and optical (AMO) physics rely on lasers at many different wavelengths and with varying requirements on spectral linewidth, power, and intensity stability. Optically pumped semiconductor lasers (OPSLs), when combined with nonlinear frequency conversion, can potentially replace many of the laser systems currently in use. Here we describe the single-frequency OPSL systems that have been developed by the NIST ion storage group. These OPSL systems are used for photoionization of neutral magnesium atoms and also for laser cooling and quantum state manipulation of trapped magnesium ions [1]. Our OPSL systems serve as prototypes for applications in AMO requiring single-frequency, power-scalable laser sources at multiple wavelengths.

[1] S. C. Burd *et al.*, *Optica*, 3, **12** (2016)

Poster No. 9**Spectroscopy on sympathetically cooled CaH^+**

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Co-trapping molecular ions with laser cooled atomic ions provides enhanced sensitivity for measuring molecular transitions with applications in astrochemistry and fundamental physics. We co-trap CaH^+ with Doppler cooled Ca^+ and perform resonance enhanced photodissociation with a mode locked Ti:Sapph laser to resolve the $1^1\Sigma, v = 0 \rightarrow 2^1\Sigma, v' = 0, 1, 2, 3$ transitions[1]. Measurements on CaD^+ confirmed the vibronic assignment[2]. Pulse shaping was then used to rotationally resolve these transitions[3].

[1] R. Rugango *et al.*, ChemPhysChem 17, **22** (2016)

[2] J. Condoluci *et al.*, arXiv:1705.01326 (2017)

[3] A. Calvin *et al.*, article in preparation

Poster No. 10

Optically resettable state manipulation of a molecular ion

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High precision spectroscopy of molecules opens windows to new fundamental physics, but remains experimentally challenging due to the complexity of molecules. For atoms, the development of quantum logic spectroscopy was a breakthrough allowing high-precision measurement for clock transitions. We are working toward adapting this recipe for measuring a rovibrational transition of AlH^+ . In our trap a Ba^+ ion co-trapped with AlH^+ is used for motional state cooling and readout of the internal state of AlH^+ . Repeated absorption events on AlH^+ causing a change in the molecular vibrational state can be mapped to a change of the motional state of Ba^+ , which can be subsequently detected. Additionally, due to its highly diagonal Franck-Condon factors AlH^+ can be optically ground state prepared. As a consequence, the entire experimental cycle including reinitialization relies on fast optical operations. We aim to achieve a repetition rate of several Hertz suitable to gather enough statistics required for high-precision spectroscopy within a few days of measurement.

Poster No. 11 **$^{133}\text{Ba}^+$: A synthetic trapped ion qubit**

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$^{133}\text{Ba}^+$ offers a nearly ideal trapped ion qubit due to its spin-1/2 nucleus, visible wavelength electronic transitions, and long-lived D states ($\tau \approx 1$ min). This radioactive isotope of barium ($t_{1/2} = 10.5$ years) has not been realized as an atomic qubit due to the incomplete spectroscopy necessary for laser cooling, state preparation, and state detection of the clock-state hyperfine and optical qubits, as well as practical challenges associated with using small quantities of radioactive materials. Using a microgram source of $^{133}\text{Ba}^+$, we load and laser cool the $A = 133$ isotope of barium II in a radio-frequency ion trap. We report the previously unknown $6^2P_{1/2} \leftrightarrow 5^2D_{3/2}$ isotope shift and $5^2D_{3/2}$ hyperfine splitting for $^{133}\text{Ba}^+$, and demonstrate the first $^{133}\text{Ba}^+$ hyperfine qubit using standard state preparation, microwave manipulation, and single-shot readout techniques for spin-1/2 atomic ions.

Advances in RF Paul traps and vacuum systems for ion clocks

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The high-quality factor ($Q=3.7\times 10^{16}$) and intrinsically low sensitivity to electromagnetic perturbations of the clock transition in $^{27}\text{Al}^+$ have enabled clock operation at an accuracy of 8.0×10^{-18} . To address inaccuracies due to time dilation and collisional frequency shifts, as well as interruptions due to aluminum-hydride formation with background gases, we are developing and testing linear Paul traps based on laser-cut, gold-sputtered diamond wafers and an ultra-high vacuum chamber made primarily out of titanium. Here we report the design and evaluation of micromotion, and time dilation shifts in two different versions of diamond wafer traps and on our progress with a third generation trap and titanium vacuum system. This work was supported by the ONR, DARPA, and ARO.

- [1] J-S. Chen *et al.*, Sympathetic Ground State Cooling and Time-Dilation Shifts in an $^{27}\text{Al}^+$ Optical Clock, *Phys. Rev. Lett.* **118** 053002 (2017)

Time-resolved observation of thermalization in an isolated quantum system

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For an isolated quantum system, the dynamics is governed by the Liouville-von Neumann equation and is, thus, unitary and reversible in time. Yet, few-body observables of (possibly highly-entangled) many-body states can yield expectation values that feature equilibration and thermalization. We study a spin coupled to a phononic environment of engineerable complexity, realized in our trapped-ion system [1]. While the total system evolves unitarily, we record the dynamics of a subsystem observable, and find the emergence of thermalization. With this time-resolved measurement, we address associated time scales of equilibration and thermalization. Further, we study the information flow between the subsystem and its environment [2].

- [1] G. Clos, D. Porras, U. Warring, T. Schaetz, *Phys. Rev. Lett.* **117**, 170401 (2016)
- [2] M. Wittemer, G. Clos, H.-P. Breuer, U. Warring, T. Schaetz, arXiv:1702.07518

Poster No. 14

System characterization of a trapped ion based quantum computer

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The characterization of fundamental qubit functions is instrumental to understanding the performance limitations for any physical qubit architecture for quantum computing. This work characterizes the performance of qubit state readout, measurement crosstalk, and single qubit gates for a $^{171}\text{Yb}^+$ qubit in a surface trap. Photons for each of the qubits in a linear chain are coupled into individual fibers in a fiber array and directed towards separate detectors for individual qubit state detection. Measurement crosstalk due to unintentional resonant scattering is characterized by measuring the coherence time of a secondary qubit shuttled varying distances from the original. Single qubit gates driven by either microwave fields or Raman transitions are characterized using gate set tomography. Progress towards characterizing two qubit gates is also reported.

Poster No. 15

Experimentally detecting the resource of fault-tolerant quantum computation by state-dependent contextuality

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Quantum computers potentially provide exponential speed-up than their classical counterparts. However, the source of the power is still elusive, which is one of the key fundamental problems in quantum information theory. It has been proved by M. Howard et al. [Nature (London) 510, 351 (2014)] that the state-dependent contextuality supplies the power of the universal fault-tolerant quantum computation through the magic state distillation. Here, using three internal levels of a single trapped $^{171}\text{Yb}^+$ ion as a qutrit, we present the first experiment to detect the resource of the fault-tolerant quantum computation by testing state-dependent contextuality inequalities in the qutrit system. Our results show that the contextuality is the key resource for quantum computation and pave the way for directly determining the power of an unknown quantum state for quantum computation.

A simple magnetometer with single trapped ion

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A single trapped and laser cooled ion provides a unique system to perform both precision measurement as well as quantum control over both its internal and external states. The suitability of a trapped ion system as a quantum sensor can hardly be ignored. We show a simple technique to achieve null magnetic field in a small special volume defined by the confinement volume of a single ion in an ion trap. Unlike, spin precision techniques, this scheme relies on continuously probing dipole transitions, thereby simplifying its implementation. The technique is based on simultaneously occurring three coherent population trapping (CPT) in a null magnetic field. A CPT by its own right is an interesting phenomena and hence it has also been studied theoretically with respect to our 18-level scheme in a singly charged barium ion. The theoretical and experimental comparison of the results clearly shows that the scheme has a potential to improve upon sensing capabilities of small magnetic fields with simple experimental setup. [1].

[1] <https://arxiv.org/pdf/1704.01070.pdf>

Poster No. 17**Characterization of the phase-noise induced by
an optical frequency doubler**

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We report on the characterization, including residual phase noise and fractional frequency instability, of second harmonic generation (SHG) fiber-coupled periodically poled LiNbO₃ (PPLN) waveguides. They are used to perform the frequency doubling from a commercially-available laser diode at a wavelength $\lambda = 871$ nm to the clock frequency of Yb⁺ at $\lambda = 435.5$ nm with an SHG efficiency up to 117.5 %/W. We observe a residual phase noise as low as -35 dBrad²/Hz at 1 Hz, which makes them compatible with the most stable up-to-date optical clocks [1] and cavities [2].

[1] M. Schioppo *et al.*, Nature Photonics 11, **48** (2016).

[2] T. Legero *et al.*, in CLEO Proceedings SW1J.1 (2017).

Progress report on $^{25}\text{Mg}^+$ trapping and cooling for a $^{25}\text{Mg}^+ - ^{27}\text{Al}^+$ quantum logic optical clock

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A $^{25}\text{Mg}^+ - ^{27}\text{Al}^+$ quantum logic optical clock [1] is under construction at Huazhong University of Science and Technology. Here we report progress on the $^{25}\text{Mg}^+$ ion trapping and cooling. First, we report an experimental determination of the ground-state hyperfine constant A of the $^{25}\text{Mg}^+$ ions through measuring the $|^2S_{1/2}, F = 2, m_F = 0\rangle$ to $|^2S_{1/2}, F = 3, m_F = 0\rangle$ transition frequency. The result is $A = -596.254\ 250(4)\text{MHz}$. Second, efficient Raman sideband cooling of $^{25}\text{Mg}^+$ ion is studied. We investigate both numerically and experimentally the optimization of Raman sideband cooling strategies. Several cooling schemes are compared through numerical simulations. Then a single $^{25}\text{Mg}^+$ is trapped in a linear Paul trap and Raman sideband cooled, the achieved average vibrational quantum numbers under different cooling strategies are evaluated.

- [1] A. D. Ludlow *et al.*, "Optical atomic clocks," *Rev. Mod. Phys.* **87**, 637 (2015).

Poster No. 19

Reactions of Ar^+ and ArH^+ ions with normal and para-enriched H_2

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A 22-pole radiofrequency ion trap was utilized to study reactions of Ar^+ and ArH^+ ions with molecular hydrogen in the temperature range of 10 – 300 K. Normal hydrogen (with para to ortho nuclear spin states ratio of 1:3) and para-enriched hydrogen (with para to ortho ratio higher than 99:1) were used in the experiments as reactant gases. The actual hydrogen para to ortho nuclear spin states ratio was obtained by measuring the endothermic reaction of $\text{N}^+ + \text{H}_2$. In case of both studied ions the change of the nuclear spin state population of hydrogen had no effect on measured reaction rate within the error of the measurement.

Poster No. 20

Capture of highly charged ions in a hyperbolic Paul trap

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We have demonstrated direct capture and storage of highly charged Ne¹⁰⁺ ions in a radio-frequency (RF) trap with hyperbolic-shaped electrodes. The electron beam ion trap (EBIT) at NIST is used to produce highly charged ions, which can then be extracted from the EBIT in an ion bunch. A specific charge state is selected by an analyzing magnet, directed by electrostatic optics into a second chamber, and recaptured at low energy by the RF trap. A systematic study investigated the dependence of the capture efficiency on the parameters of the RF drive, including the phase of the RF electric field relative to the ion arrival time at the trap. The experimental results and simulations will be compared. Refinements of this technique may be useful in precise spectroscopic studies of weakly-allowed transitions in highly ionized atoms for developing novel atomic clocks, searching for time-variation of the fine-structure constant, and determining fundamental constants.

Poster No. 21

Entanglement transfer via a programmable ion-photon interface

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We are developing experimental tools, based on trapped-ion and photonic technologies, that enable controlled generation, storage, transmission, and conversion of photonic qubits in a quantum network. Specifically, we implemented a programmable atom-photon quantum interface, employing the quantum interaction between a single trapped $^{40}\text{Ca}^+$ ion and single photons [1]. Depending on its mode of operation, the interface serves as a bi-directional atom-photon quantum-state converter or as a source of entangled atom-photon states. As an experimental application, we demonstrate the transfer of qubit entanglement from SPDC photon pairs to atom-photon pairs. We also observe signatures of entanglement between an atomic ion and a single telecom photon, after controlled emission of a single photon at 854 nm and its quantum frequency conversion into the telecom band.

[1] C. Kurz et al., Nat. Commun. 5, 5527 (2014).

C. Kurz et al., Phys. Rev. A 93, 062348 (2016).

Chained Bell inequality experiment with high-efficiency measurements

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Several groups have recently performed loop-hole free violations of Bell's inequality, rejecting with high confidence theories of local realism. However, these experiments are limited in the extent to which their results differ from local realism. Observed correlations can be modeled as arising from a mixture of a local-realistic probability distribution and a maximally nonlocal distribution. Using a pair of entangled Be⁺ ions to test the chained Bell inequality (CBI), we put an upper bound of 0.327 on the local-realistic fraction with 95% confidence. This is significantly lower than 0.586, the lowest possible upper bound attainable from a perfect Clauser-Horne-Shimony-Holt inequality experiment. Furthermore, this is the first CBI experiment to close the detection and memory loopholes and the first on massive particles [1]. This work was supported by IARPA and the NIST quantum information program.

[1] T. R. Tan *et al.*, *Phys. Rev. Lett.* **118**, 130403 (2017)

Poster No. 23

Improving stability and modeling noise in ion experiments

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We report on progress towards an atomic clock based upon two chains of twenty $^{171}\text{Yb}^+$ ions. Ion state detection is interleaved such that only one chain is transported into the detection beam at a time. Simulation results indicate that interleaved measurement can improve clocks limited by local oscillator stability [1, 2].

Additionally, we highlight software modifications made to the digital-servo controller developed by the NIST Ion Storage Group [3]. We incorporate software to inject Gaussian-distributed noise onto ion trap controls (e.g. laser amplitude). A reconfigurable digital figure is used to modify the spectra of this noise. In this way, accompanying error simulation tools can be verified.

- [1] J. Borregaard and A. S. Sorensen, Phys. Rev. Lett. 090802, **111** (2013)
- [2] T. Rosenband and D. R. Leibbrandt, arXiv: 1303.6357 (2013)
- [3] D. R. Leibbrandt and J. Heidecker, Rev. Sci. Instrum. 123115, **86** (2015)

MEMS-based beam steering for scalable quantum gate operations with trapped ion qubits

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The potential for trapped atomic ions to serve as a scalable quantum computing platform relies on the capability to individually address each ion in order to perform a complete set of single-qubit and fully connected two-qubit gates. We present an experimental system where $^{171}\text{Yb}^+$ ions in a surface trap are addressed by two tightly focused laser beams and a counter-propagating global beam to drive Raman transitions. The two individual addressing beams can be independently steered in two dimensions using tilting microelectromechanical systems (MEMS) mirrors [1]. The optical system design enabling high fidelity single-qubit gates and two-qubit gates is described and characterized. The digital control systems for stabilizing the optical frequency combs used to drive gate operations and for actuating the MEMS mirrors are outlined.

[1] S. Crain *et al.*, Appl. Phys. Lett. **105**, 181115 (2014)

Poster No. 25**Trapping ions in an optical lattice for quantum simulation**C. Fischer¹, O. Wipfli¹, M. Grau¹, J. P. Home¹¹Institute for Quantum Electronics, ETH Zurich, Otto-Stern-Weg 1,
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The intrinsic long-range Coulomb interaction and precision control techniques make ensembles of atomic ions attractive candidates for simulation of quantum many-body spin systems. To date, efforts in this direction have worked with limited geometry, either linear strings of ions in rf Paul trap [1] or self-assembled Coulomb crystals confined in Penning traps [2]. We are developing an apparatus to trap two-dimensional arrays of magnesium ions in the far off-resonant standing-wave optical potential of a high-finesse enhancement cavity. Numerical simulations indicate that it is feasible to trap around 40 ions with inter-ion spacing of less than $10\ \mu\text{m}$. I will present the current progress of the experiment as well as calculations of the normal mode structure and heating rates.

[1] C. Senko *et al.*, Phys. Rev. X **5**, 021026 (2015).

[2] J. W. Britton *et al.*, Nature **484**, 489 (2012).

Observation of cold collisions between Li and Yb^+

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Recent experiments have shown that the ion trapping RF-field can cause heating in hybrid atom-ion systems [1]. A way to mitigate this problem is to employ ion-atom combinations with a large mass ratio [2], e. g. Yb^+ and ${}^6\text{Li}$. We present experimental results on cold collisions between these species. For atoms and ions prepared in the $S_{1/2}$ ground state, inelastic collisions are suppressed by more than 10^3 compared to the Langevin rate, in agreement with theory [3]. The prospects of using ${}^6\text{Li}$ and Yb^+ in atom-ion experiments aiming at sympathetic cooling or quantum information technology are therefore excellent. Further we present data on inelastic collision rates for excited electronic states of the ion, as well as preliminary results on the dynamics of the ${}^{171}\text{Yb}^+$ hyperfine spin impurity within the ${}^6\text{Li}$ gas.

[1] Z. Meir *et al.*, Phys. Rev. Lett. 117, **243401** (2016)

[2] M. Cetina *et al.*, Phys. Rev. Lett. 109, **253201** (2012)

[3] M. Tomza *et al.*, Phys. Rev. A 91, **042706** (2015)

Poster No. 27

Scalable quantum computation - keeping a qubit alive

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Trapped ions are a promising platform for implementing a quantum computer. In our setup we use a planar trapping architecture in a cryostat to demonstrate scalable quantum computation. The setup has been designed to limit magnetic field noise and mechanical vibrations which both can induce errors. Two species, $^{40}\text{Ca}^+$ and $^{88}\text{Sr}^+$, are co-trapped, allowing for recooling of ion crystals during sequences. Recently, ion crystal reconfigurations of both single and multi species ion crystals have been achieved with only few phonons accumulated per rotation. These swaps expand the toolbox available in the future.

Measuring entanglement and many-body correlations with a hundred-ion quantum simulator

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We describe quantum simulations of a network of interacting magnetic spins performed with 2D arrays of hundreds of Be^+ ions in a Penning trap. We engineer a tunable transverse Ising model, and generate and observe far-from-equilibrium quantum spin dynamics, including signatures of entanglement. We summarize the experimental demonstration of a measurement protocol motivated by the multi-quantum coherence (MQC) protocol of NMR, enabling us to measure the buildup of many-body correlations [1]. The protocol is based on the time reversal of the all-to-all Ising interactions, and is equivalent to measuring an out-of-time-order correlation (OTOC), which has been proposed as a means of measuring the scrambling of quantum information.

[1] M. Gärttner *et al.*, Nat. Phys. (2017) doi:10.1038/nphys4119

Poster No. 29

Quantum state controlled, radical-ion reactions

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Radical-Ion reactions contribute to the growth of larger molecular species observed in the interstellar medium (ISM). To probe the underlying ISM chemistry, experiments dedicated to understanding radical-ion reactions are needed. We present a state-controlled reaction between the Ca^+ cation and the neutral radical NO. We utilized a linear ion trap, radially coupled to a time-of-flight mass spectrometer (TOFMS). This apparatus enabled direct measurements of multiple ionic product channels, simultaneously, with sensitivity down to the single ion level. We also demonstrate quantum control over the reaction via the excited state populations of laser cooled $^{40}\text{Ca}^+$. Combining quantum control and sensitive detection methods enables a precise measurement of the reaction kinetics.

Sympathetic cooling of ${}^9\text{Be}^+$ by ${}^{88}\text{Sr}^+$ Doppler cooled ions in large Coulomb crystals: an experimental study

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We study large multispecies Coulomb crystals in the case of a heavy coolant (${}^{88}\text{Sr}^+$) and a light cooled species (${}^9\text{Be}^+$), extending previously reported mass ratios [1]. This system has an interest for future experiments on highly charged ions [2] and on antimatter sympathetic cooling [3].

[1] B. Roth *et al.*, Phys. Rev. A, **75** 023402 (2007).

[2] L. Schmoger *et al.*, Science, **347** 1233 (2015).

[3] P. Perez and Y. Sacquin, Classical and Quantum Gravity, **29** (2012).

Poster No. 31**Applications of the trilinear Hamiltonian with three trapped ions**

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The realization of a coupling among harmonic oscillators characterized by the trilinear Hamiltonian $a^\dagger b c + a b^\dagger c^\dagger$ opens possibilities to study and simulate quantum systems ranging from basic models to thermodynamics. This coupling is naturally present between three modes of motion in a system of three trapped $^{171}\text{Yb}^+$ ions due to their mutual (anharmonic) Coulomb repulsion. By tuning our trapping parameters we are able to manipulate the resonant exchange of energy between these modes on demand. We present applications of this Hamiltonian for simulations of the parametric down conversion process in the regime of depleted pump, a simple model of Hawking radiation, and the Tavis-Cummings model. We also discuss the implementation of the quantum absorption refrigerator in such system and experimentally study effects of quantum coherence on its performance [arXiv:1702.08672].

Towards telecom photons entangled with Ba⁺

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Networking remote trapped ion quantum memories involves collection, propagation and detection of photons entangled with internal qubit states [1]. Substantial attenuation of photons propagated through optical fibers occurs at the ion's wavelength, limiting the network's range. A promising solution to this is quantum frequency conversion (QFC), where short wavelength ion-photons (493 nm and 650 nm for Ba⁺) are converted into long wavelength telecom-photons. We aim to produce telecom photons entangled with a single Ba⁺ ion using either one or two stage conversion in a nonlinear (PPLN) waveguide [2]. This could enable hybrid quantum networking between ions and neutral atoms. Here we demonstrate QFC tuned to the Ba⁺ resonant wavelength of 650 nm using a pump at 1343 nm to produce telecom photons. We also characterize our ytterbium and barium dual species ion trap designed for single photon extraction. [1] C. Monroe *et al.*, Phys. Rev. A, **89**, 022317 (2014) [2] J. D. Siverns *et al.*, Appl.Opt., **56**, B222-B230 (2017)

Poster No. 33**A novel ion cooling process using autoresonance
in an electrostatic ion beam trap**

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A new method of evaporative cooling of a bunch of ions oscillating inside an electrostatic ion beam trap is presented. The relatively wide initial longitudinal velocity distribution is reduced by at least an order of magnitude well below 1K, using autoresonance (AR) acceleration and ramping forces. The evaporated hot ions are not lost from the system, but continue to oscillate outside of the bunch and may be further cooled by successive AR processes or can be ejected out from the trap. Ion-ion collisions inside the bunch close to the turning points in the trap's mirrors contribute to the thermalization of the ions. This evaporative cooling method can be applied to any mass and any charge. Preliminary data indicates that similar process can affect also the ro-vibration distribution of molecular ions[1].

[1] R. K. Gangwar *et al.*, Submitted to Physical Review Letters.

Investigation of charging effects of exposed dielectric surfaces in surface ion-trap chips

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Trapped ions are highly sensitive to the built-up charges on surrounding dielectric materials. This problem has become more recognized as interests in surface ion traps have increased in recent years. In general, in surface ion traps, ions are confined very close to chip surfaces, which generally have electrodes that are separated by dielectric surfaces. To reduce the built-up charges, a surface ion-trap chip with metal coating on the sidewalls of dielectric pillars is presented in this paper. Three versions of trap chips are microfabricated. The first version has exposed bare dielectric side surfaces. The second version covers the dielectric side surfaces with sputtered Al. The third version further covers the Al with sputtered Au. To investigate the charging effects, the displacement of ion position is measured after injecting 355-nm ultraviolet (UV) laser to the chip surface. This paper presents qualitative comparisons among the three types of trap chips.

Poster No. 35

Nondegenerate elliptical fiber Fabry-Perot cavities with large tunable splitting

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We report a novel method for fabricating a fiber Fabry-Perot cavity (FFPC) with elliptical concave mirrors which have controllable eccentricity ranging from 0.1 to 0.72. The elliptical cavity combines the advantages of high finesse up to 40000 and tunable polarization modes splitting up to 3.2 GHz. Our experiment reveals that elliptical cavities can fully exploit the photon polarization degree of freedom including modes transmission and modes splitting. It will be suitable for a wide range of applications where nondegenerate polarization modes are required, including experiments on cavity quantum electrodynamics (CQED), cavity optomechanics, and techniques such as cavity spectral engineering, cavity locking and polarization optical filters.

An error-corrected, universal, re-configurable, ion-trap quantum archetype

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The EURIQA project is a collaboration between universities and industrial partners implementing a systematic, top-down approach to constructing a complex quantum processor capable of executing quantum error correction, with the goal of realizing an encoded logical qubit on a trapped-ion platform. Although trapped ions provide the most promising platform on which one can build a logical qubit [1], the qubit number and complexity of quantum circuits presents several key challenges. We will present the status of the state-of-the-art system development underway at JQI/UMD to address all of these challenges, including: micro-fabricated traps, individual addressing, multi-species chains, vacuum, lasers, controllers, and system integration.

[1] N. M. Linke *et al.*, Proc. Natl. Acad. Sci. 114, **13** (2017)

Poster No. 37

Toward ground state cooling of hundreds of ions in a Penning trap

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Systems of trapped ions have made substantial progress as simulators of quantum magnetic systems. We perform quantum simulations of the transverse Ising model using a 2-dimensional crystal of hundreds of Be^+ ions in a Penning trap. The Ising interaction is implemented by a spin-dependent optical dipole force generated from the interference of a pair of detuned lasers. We summarize initial experiments that apply adiabatic protocols for preparing low energy states of the transverse Ising Hamiltonian. To further improve the fidelity of the simulations we plan to implement EIT cooling of the transverse drumhead modes of the ion array. The rotation of the array complicates this implementation, but simulations indicate that cooling close to the ground state can be achieved.

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Poster No. 38

Attainable accuracy of vibrational transition frequencies of homonuclear diatomic molecular ions

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The attainable accuracies of $N_2^+ X^2\Sigma(v, N) = (0, 0) - (v', 0)$ and $O_2^+ X^2\Pi_{1/2}(v, J) = (0, 1/2) - (v', 1/2)$ ($v' \geq 1$) transition frequencies are discussed in this presentation. Seeing the Zeeman shift ($< 2 \times 10^{-15}/G$), the blackbody radiation shift (with $300 K < 4 \times 10^{-18}$), and the electric quadrupole shift (zero), the attainable accuracy might be higher than the transition frequencies of Al^+ ion and Sr atom. Precise measurement of the vibrational transition frequencies is useful to search the variation in the proton-to-electron mass ratio. [1].

[1] M. Kajita, Phys. Rev. A **95**, 023418 (2017)

Poster No. 39

Sinara: open source modular hardware for quantum physics

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The Sinara hardware platform is modular open source measurement and control system dedicated to quantum applications that require hard real time performance. It is based on standard, industry-proven MTCA.4 and Eurocard Extension Modules (EEM).

The hardware modules can be combined in several configurations, starting from low cost single box device attached to PC up to experiment control systems covering all needs of complex laboratory setup. The hardware is controlled and managed by the ARTIQ software developed by M-Labs. The software is open-source, high-level programming language that enables describing complex experiments with nanosecond timing resolution and sub-microsecond latency. The system currently consists of over 20 different modules and other ones are under development [1].

[1] <https://github.com/m-labs/sinara/wiki>

Toward quantum simulations with ions in 2D microtrap arrays

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Two-dimensional systems of interacting particles support the emergence of a whole range of interesting many-body phenomena. While trapped-ion quantum simulations have so far been restricted to the geometries and couplings available in self-assembled systems, the demonstration of sufficiently strong Coulomb coupling between ions in separate potential wells [1] has opened up the possibility for a much more flexible approach based on microtrap arrays. Besides lifting geometrical restrictions, this concept also allows for individual control over the coupling terms between sites. In a collaboration with the Schätz group and Sandia National Labs [2], we are working toward an implementation of all necessary ingredients for this approach, starting with demonstrations on three mutually coupled ions.

[1] Brown *et al.*, Nature 471, **196** (2011); Harlander *et al.*, Nature 471, **200** (2011)

[2] Mielenz *et al.*, Nature Communications 7, **11839** (2016)

Poster No. 41

Spectroscopy and transport of topological solitons in Coulomb crystals

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We investigate trapped atomic ions as a platform for quantum simulations. Although one-dimensional systems have delivered groundbreaking results, scaling to larger size and dimension presents a major challenge. On the one hand, we follow a bottom-up approach of single ions in individually controlled trapping sites generated by microfabricated two-dimensional trap arrays.

On the other hand, we investigate planar Coulomb crystals with a size of several tens of ions, confined in a conventional linear Paul trap. Topologically protected structural defects therein, so called kinks, feature the properties of discrete solitons. In this presentation I focus on the resonant and spatially localized excitation of the kinks on a gapped vibrational mode. This leads to a directed transport of the defect inside the ion crystal depending on its conformation.

Poster No. 42

Quantum networks with single trapped ions in fiber cavities

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We work towards the demonstration of an elementary quantum network with Yb^+ ions coupled to fiber cavities. Due to their small mode-volume, these cavities offer a large coupling between a single ion and a single photon.

We recently demonstrated a UV fiber-cavity which is coupled to the S-P electric dipole transition of Ytterbium at 369.5 nm [1]. In combination with coherent control of the atomic state, this constitutes an elementary, directly fiber-coupled quantum network node.

[1] T. G. Ballance *et al.*, Phys. Rev. A **95**, 033812 (2017)

Poster No. 43

Preparation and coherent manipulation of pure quantum states of a single molecular ion

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We demonstrate control of individual molecules based on quantum-logic spectroscopy [1]. We drive the motional sidebands of Raman transitions in a molecular ion and probe the secular motion with a co-trapped atomic ion. Detection of motional excitation projects the molecule into a pure internal state which can then be coherently manipulated, as shown by Rabi oscillations between rotational sublevels in either the same or distinct rotational manifolds. We use one continuous-wave laser and one frequency comb [2], far off-resonant from any electronic transition, to manipulate the molecule. This makes our approach suitable for a large number of molecular species.

[1] C.-w. Chou *et al.*, *Nature* **545**, 203 (2017)

[2] D. Leibfried, *New J. Phys.* **14**, 023029 (2012)

Ion motional heating rate on a high-temperature superconducting YBCO surface trap

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Surface ion traps are a promising platform for quantum computation [1]. However, the proximity of the ions to the trap's surface affects the heating rate of the motional state. The origin of this heating is not clear so far. To investigate this topic we use a surface ion trap made of YBCO. The trap is designed in such a way that Johnson noise (JN) is the dominant source of heating above the critical temperature T_c , whereas below T_c it should be negligible. We observe an increase of about 300 times in the heating rate across the superconducting transition. This observation is consistent with the expected value for the JN above T_c . Below T_c , the frequency scaling of the electric field noise is in agreement with a dipole fluctuator noise source.

[1] R. Blatt and D. Wineland, Nature 453, **1008** (2008)

Poster No. 45**Single ion imaging and fluorescence collection
with a parabolic mirror trap**J. F. Lilieholm¹, C. K. Chou¹, C. Auchter¹, K. Smith¹, and B. Blinov¹¹University of Washington, Seattle, WA 98195

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A parabolic mirror trap can be used to obtain a greater light collection efficiency from trapped ions. This trap is a permutation of the well known Paul trap, which uses a ring and two endcaps with an applied voltage. The ring can be deformed into a parabolic mirror, which allows for increased light collection. Previously, we used a spherical mirror to collect light from roughly 25% of the solid angle surrounding the ion; with the parabolic mirror trap the efficiency is about 39% of the solid angle.

Although the collection efficiency is greatly increased, ion micromotion causes the ion image to form 2.8 times greater than the diffraction limit. A second parabolic mirror trap has been built containing piezoelectric actuators along the needle guide, which will allow greater control over the needle position to minimize ion micromotion [1].

- [1] C. K. Chou *et al.*, arXiv preprint arXiv:1701.03187, accepted to Review of Scientific Instruments

Quantum simulation of the quantum Rabi model in a single trapped ion

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The quantum Rabi model describes the fundamental light-matter interaction of the dipolar coupling between a two-level system and a bosonic field mode. Several physical systems have been pursued to implement the perturbative regime of ultrastrong coupling. However, it is still challenging to reach the dynamics of the nonperturbative ultrastrong coupling regime and the deep-strong coupling regime, which would show intriguing physical phenomena beyond intuitive features of the quantum Rabi model. Here, we implement the quantum simulation of the paradigmatic quantum Rabi model in a trapped-ion system, reproducing key features of all parameter regimes from the weak to the deep-strong coupling regimes.

Poster No. 47

Quantum and classical control of ions in Sandia's HOA trap

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Trapped-ion quantum information experiments have reached ion numbers where precise control of multiple ion chains is necessary, resulting in a growing need for high-performance microfabricated surface traps.

With Sandia's High Optical Access (HOA) trap, which boasts high trap frequencies and long trapping times, we have achieved the first single-qubit gates with a diamond norm below a rigorous fault tolerance threshold [1, 2], and a two-qubit Mølmer-Sørensen gate [3] with a process fidelity of 99.58(6). We also demonstrate novel control techniques, afforded by precise manipulation over the curvature of the trapping potential, that support continuous rotation of principal axes while maintaining constant secular frequencies.

- [1] R. Blume-Kohout *et al.*, Nature Communications **8**, 14485 (2017).
- [2] P. Aliferis and J. Preskill, Phys. Rev. A **79**, 012332 (2009)
- [3] A. Sørensen and K. Mølmer, Phys. Rev. Lett. **82**, 1971 (1999)

Verification of quantum non-equilibrium work and fluctuation relations in the presence of decoherence

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We report on an experimental test of non-equilibrium work and fluctuation relations with a single $^{171}\text{Yb}^+$ undergoing decoherence. Although these relations have been fully studied within classical physics, extending them to open quantum system is still conceptually difficult. However, for systems undergoing decoherence but not dissipation, we argue that it is natural to define quantum work exactly as for isolated quantum systems. Our experimental results reveal the work relations' validity in this situation, over a variety of driving speeds, decoherence rates, and effective temperatures and represent the first confirmation of the work relations for non-unitary dynamics.

Quantum simulation of molecular spectroscopy with trapped ion

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Simulation of molecular systems is one of important applications of quantum computers since it is greatly demanded but generally intractable in classical computer. The recent theoretical proposal of Ref.[1] showed that a multi-photon network with Gaussian input states can simulate a molecular spectroscopic process. Here, we report the first experimental demonstration of molecular vibrational spectroscopy of SO₂ with a trapped-ion system. In our realization, the molecular scattering operation is decomposed to a series of elementary operations including displacements, squeezing, and mode-mixings, resulting in a multimode Gaussian (Bogoliubov) transformation. The molecular spectroscopic signal is reconstructed from the collective projection measurements on phonon modes of ion. Our experimental demonstration would pave the way to large-scale molecular quantum simulations.

[1] J. Huh *et al.*, Nature Photonics. 9, **615** (2015)

Fabrication of ion-trap electrodes by self-terminated electrochemical etching

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Self-terminated electrochemical etching is applied to fabricate needle electrodes for ion traps. We study the surface morphology of the electrodes with scanning electron microscopy and atomic force microscopy, and find that the surface curvature and roughness can be reduced by optimizing the etching parameters. Our method provides a convenient and low-cost solution to improve the surface quality of electrodes for ion traps.

Poster No. 51

Scalable cryogenic experiment for trapped-ion quantum computing

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I will describe two areas of development towards scaling up ion trap quantum computers. In the first, which comprises a theoretical design study, I have investigated new trap designs for performing multi-qubit control using only microwave (MW) fields. This would obviate the need for high power control lasers and may be easier to scale. In the second part, I will describe the development of a new cryogenic apparatus for testing new technologies for ion trap control. In the first instance we plan to trap up to 12 ions in a micro-fabricated trap as part of a project to demonstrate a real advantage in quantum error correction. Design considerations as well as experimental progress will be discussed.

Poster No. 52

Bounding the quantum process fidelity with a minimal set of input states

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We investigate the problem of bounding the quantum process fidelity when given bounds on the fidelities between target states and the outputs of a process acting on a set of pure input states. For arbitrary input states, we formulate the problem as a semidefinite program, and we prove convexity of the minimal process fidelity as a function of the input state errors. We characterize the conditions required to uniquely determine the process in the case of no errors. Finally, we introduce a set of $d + 1$ pure states which form a symmetric and informationally undercomplete POVM for which the minimum fidelity scales linearly with the average state error. We analytically prove the lower bound for these states, which allows for efficient estimation of the process fidelity without the use of full process tomography.

Poster No. 53

Integrated technologies for chip-scale trapped-ion quantum control

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Ions confined in microfabricated surface-electrode trap arrays represent a promising system for scalable quantum information processing. However, the difficulty of independent control and laser-beam-addressing of larger numbers of ions is an obstacle to genuine scalability. Standardized foundry processes may overcome these issues by allowing fabrication of surface-electrode traps with integrated photonic devices and CMOS electronics, performing the key functions of a quantum information processor on-chip. Here we describe progress towards the demonstration of essential components of an integrated chip-scale platform, focusing on multilayer photonic waveguides to route multiple laser beams throughout a trap array, integrated photo-detectors for ion-state readout, and embedded CMOS circuitry for on-chip electronic control.

Towards a 2-D trapped-ion quantum simulator

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Two-dimensional arrays of trapped ions offer new possibilities for quantum simulation. Each ion is trapped in a separate, individually controllable potential well, making interactions between ions tunable and different conformations of ions possible. In most trapped ion quantum simulation proposals, exchange of phonons mediated by the Coulomb interaction serve as the information bus between ions, so precise control of each ion's motion is imperative. Recently, we have performed experiments aimed at developing and characterizing the necessary level of control. I will present our ongoing efforts in generating non-classical states of motion and using these states to develop a phonon interferometer that detects trap frequency fluctuations with sensitivity below the standard quantum limit.

Poster No. 55

State controlled ion-neutral reactions

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By studying cation-neutral reactions, we can investigate chemistry that is relevant for a wide range of environments including the interstellar medium and earth's upper atmosphere. We present results from the following reaction $^{40}\text{Ca}^+ + \text{O}_2 \rightarrow \text{CaO}^+ + \text{O}$. To study this reaction, we trap laser-cooled Ca^+ in a linear quadrupole trap. Coupled to the trap is a TOF-MS with mass resolution >1000 and single ion detection sensitivity. The combination of the quadrupole trap and the TOF-MS allows us to probe reaction products. By adjusting the excited-state population of Ca^+ , we can measure changes in the reaction rate and characterize the kinetics of the reaction.

Two-qubit entanglement with ultrafast laser pulses

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In contrast to gates that operate in the resolved sideband regime, a sequence of ultrafast laser pulses that impart spin-dependent momentum kicks (SDKs) can be used to create entangling gates that are faster than a trap period. These gates can operate outside of the Lamb-Dicke regime, making them much less sensitive to thermal atomic motion and more easily scalable to large systems [1]. As a proof of principle experiment, we have implemented a sequence of SDKs to realize a fully entangling phase gate between two trapped $^{171}\text{Yb}^+$ ions, using only 10 laser pulses. We verify entanglement by applying the pulse sequence within a Ramsey interferometer and measuring the resulting parity oscillation. The total gate duration is about $20\ \mu\text{s}$, set by the amount of trap evolution required to achieve the desired gate phase. The best achieved fidelity is $(76 \pm 1)\%$, limited by the SDK fidelity. Future work includes studying the limitations of the SDK fidelity and speeding up the gate sequences by switching the direction of successive SDKs.

[1] J. Mizrahi *et al.*, Applied Physics B **114**, 45 (2014).

Poster No. 57

Testing a dual-anode miniature electron beam ion trap for the production of highly charged ions

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Recent theoretical studies indicate that certain highly charged ions (HCI), such as Pr^{9+} and Nd^{10+} , are potentially useful for interesting applications, such as the development of next-generation atomic clocks, quantum information, or the search for variation in the fine-structure constant [1]. At NIST, highly charged ions can be extracted from an electron beam ion source/trap (EBIS/T) with a strong magnetic field (~ 3 T). However, lower magnetic fields and compact geometry are more suitable for abundantly producing the proposed candidate ions with ionization thresholds ranging from 100 eV to 1000 eV. We are developing a room-temperature miniature EBIT (mini-EBIT) with a dual-anode electron gun, which can alleviate the space charge effects for the lower electron beam energy. This work presents new features in this dual-anode mini-EBIT and preliminary results on the extraction of HCI.

[1] M. Safronova *et al.*, PRL 113, **030801** (2014)

Repeated multi-qubit parity measurement, feedback and stabilization using a mixed-species ion crystal

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Multi-qubit nondemolition parity measurements are critical for feedback-based quantum error correction, as well as a powerful building block in QIP and metrology protocols. By measuring the parity of two beryllium ions through a calcium ancilla in a laser-phase insensitive block, then applying low-latency conditional feedback, we can deterministically stabilize odd- and even-parity subspaces as well as generating Bell states from any state preparable with global operations. Sympathetic recooling of the 3-ion crystal using the ancilla facilitates up to 50 rounds of QND measurement and feedback. We have also run new Bayesian protocols to rapidly calibrate single-qubit parameters, achieving comparable accuracy to non-Bayesian calibration techniques [1] with shorter experiment times. We are grateful for funding from ETH Zürich, the Swiss National Science Foundation, and IARPA.

[1] K. Rudinger *et al.*, Phys. Ref. Lett. **118**, 190502 (2017)

Poster No. 59

Preparation of Grid state qubits by sequential modular position measurements of trapped ions motion

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We use sequential measurements of modular position and momentum in the oscillatory motion of a single trapped ion to analyse their commutative nature. With incompatible measurement settings, we are able to exclude macro-realistic theories by observing the Signaling In Time (SIT) and violating the Leggett-Garg inequality. The commutation of these modular variables allows their use as stabilizers for fault-tolerant continuous variable computation [1]. Combining the control over these sequential measurements with the ability to prepare squeezed states [2] we are able to prepare and readout the approximate code states (Grid states). I will show our preliminary results as well as how to implement single qubit operations.

[1] D.Gottesman *et al.*, Phys. Rev. A 64, **012310** (2001)

[2] D. Kienzler *et al.*, Science 347, **6217** (2015)

Frequency measurement of the clock transition of In^+ ion sympathetically-cooled with Ca^+ ions

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Since the clock transition frequency for In^+ has low sensitivity to external fields, fractional frequency uncertainty is expected to reach 10^{-18} level. Relatively wide linewidth (360 kHz) of $^1\text{S}_0$ - $^3\text{P}_1$ transition permits the direct quantum state detection which allows clock measurement easier. Due to these spectroscopic features, In^+ is a promising candidate of the multi-ion optical clock with enhanced stability. We report frequency measurement of the clock transition in an In^+ ion which is sympathetically-cooled with Ca^+ ions in a linear rf trap. In our new approach, Ca^+ ions are used for coolant ions as well as a probe for the trapping and surrounding fields to compensate slow scattering rate of the $^1\text{S}_0$ - $^3\text{P}_1$ transition. The frequency is determined to be 1 267 402 452 901 049.9 (6.9) Hz by averaging 36 measurements[1].

[1] N. Ohtsubo, *et al.*, Optics Express, **25**, 11725 (2017)

Poster No. 61**Towards quantum logic inspired cooling and detection for single (anti-)protons**

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We discuss laser-based and quantum logic inspired cooling and detection methods amenable to single (anti-)protons for a g-factor based test of CPT invariance currently pursued within the BASE collaboration [1]. Towards this end, we explore sympathetic cooling of single (anti-)protons with ${}^9\text{Be}^+$ ions [2]. We discuss the setup of a cryogenic Penning trap experiment built for this purpose, including laser systems and detection.

[1] C. Smorra *et al.*, EPJ-ST **224**, 1 (2015)

[2] D. J. Heinzen and D. J. Wineland, Phys. Rev. A **42**, 2977 (1990)

Shortcuts to adiabaticity for fast operations with trapped ions

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The coherent manipulation of trapped ions for information processing, simulations, or metrology requires sequences of basic operations such as transport [1], expansions/compressions [2], separation/merging of ion chains [3], rotations [4], or one and two-qubit gates [5]. Shortcuts to adiabaticity (STA) based on dynamical invariants provide fast protocols to perform these operations without final motional excitation. The applications of STA to trapped ions [6] and prospects for further work are reviewed.

[1] M. Palmero *et al.*, Phys. Rev. A **90**, 053408 (2014).

[2] M. Palmero *et al.*, Phys. Rev. A **91**, 053411 (2015).

[3] M. Palmero *et al.*, New J. Phys. **17**, 093031 (2015).

[4] M. Palmero *et al.*, New J. Phys. **18**, 043014 (2016).

[5] M. Palmero *et al.*, Phys. Rev. A **95**, 022328 (2017).

[6] I. Lizuain *et al.*, Phys. Rev. A **95**, 022130 (2017).

Poster No. 63

A path to polyatomic molecular ions in single quantum states

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Polyatomic molecular ions are attractive systems for a broad range of quantum science applications, including precision measurement, quantum information processing, and single molecule chemical and chiral analysis. To date we lack the tools to initialize and read out the internal state of these ions. We propose a general method of preparing and detecting polyatomic molecular ions in single internal states. Counterintuitively, polyatomics may well be easier to manipulate and cool than diatomics such as CaH^+ . Molecules are first trapped, buffer gas cooled to ~ 10 K, and motionally cooled to mK via co-trapped laser cooled Sr^+ ions. Internal (rotational) transitions are driven both electrically and via far off-resonant optical fields modulated at microwave frequencies. These optical fields can be spatially modulated, allowing agile control of the coupling between ion motion and internal states. The methods rely only on established ion-trapping techniques and the near-universal anisotropic polarizability of asymmetric molecules, and demand far less stringent engineering than related quantum logic spectroscopy schemes.

VECSEL – a versatile laser tool for ion trappers

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Vertical-external-cavity surface-emitting lasers (VECSELs, aka. OPSLs or SDLs) [1] are versatile lasers combining the wide spectral coverage of semiconductor gain media with the flexibility offered by optically pumped solid-state disk laser architectures. The benefits of VECSELs have been recently leveraged to ion trapping with the demonstration of a trapping system fully based on these novel light sources [2]. Here we present a compact narrow-linewidth VECSEL prototype platform developed for applications in atomic and molecular physics. In particular, we display a 1118 nm system suitable for Doppler cooling of Mg⁺ ions. We also review the wavelength coverage of VECSELs for other atomic lines and discuss future development possibilities.

[1] M. Kuznetsov *et al.*, IEEE J. Sel. Top. in Quant. Electronics 5, 3 (1999)

[2] S. Burd *et al.*, Optica 3, 12 (2016)

Poster No. 65

Microfabricated microwave-integrated surface ion trap

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Single hyperfine qubit addressing, while typically accomplished using an optical Raman transition, has been demonstrated using microwave fields [1]. By integrating the microwave electrode into the trap surface the field strength is increased which enables faster gates compared to far field. Strong near-field microwave radiation is necessary for multiple single ion gates and towards using gates with gradient fields [2]. Using Sandia's microfabrication techniques, we manufactured a multi-layered surface ion trap with collocated microwave antennae and ion trap electrodes. Here, we characterize the trap design and present simulated microwave performance with current experimental results.

- [1] D. P. L. Aude Craik, *et al.*, *Appl. Phys. B* **114**, 3 (2014)
[2] T. P. Harty, *et al.*, *PRL* **117**, 140501 (2016); U. Warring *et al.*, *PRL* **110**, 173002 (2013)

Experimental study of endothermic isotope exchange at low temperatures

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We present a study of the endothermic isotope exchange $\text{OD}^- + \text{H}_2 \rightarrow \text{OH}^- + \text{HD}$, $\Delta H = 24 \text{ meV}$ using a cryogenic radiofrequency 22-pole trap at temperatures between 10 K and 300 K. We have studied this reaction previously [1] with normal hydrogen, where the internal energy of H_2 effectively reduces the reaction endothermicity to approximately 9 meV. In order to observe the true reaction endothermicity, we have now carried out measurements with para-hydrogen. The endothermicity obtained from the present data is in agreement with values expected from spectroscopic data and it can be used to provide constraints on the isotopic electronic shift between OH^- and OD^- . Furthermore, our results can be used to infer information about the thermalization of ions in the trap.

[1] D. Mulin *et al.*, Phys. Chem. Chem. Phys. **17**, 8732–8739 (2015)

Poster No. 67**A compact Penning trap frequency reference**

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Large-scale Penning traps operating within superconducting magnets have proven useful for a variety of trapped charged-particle experiments including quantum simulation, mass spectrometry, precision metrology, molecular spectroscopy, and measurements of fundamental constants. Unitary Penning traps built with permanent magnets have recently been demonstrated for storage and spectroscopy of highly-charged ions [1]. Passive ion confinement combined with the absence of micromotion make compact Penning traps potentially attractive as portable frequency references. We will present progress towards initial trapping of $^{40}\text{Ca}^+$ ions in a NdFeB-based Penning trap optimized for a uniform, stable magnetic field of ~ 1 T. *This work is funded by the Office of Naval Research.

- [1] N. D. Guise, J. N. Tan, S. M. Brewer, C. F. Fischer, and P. Jönsson, *Phys. Rev. A* **89**, 040502 (2014)

Fast entangling gates with trapped ions

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All experimentally demonstrated trapped-ion entangling gates are fundamentally limited to speeds well below the motional frequencies. Many schemes have been proposed to overcome these limitations - for example [1, 2, 3] - but none has been successfully implemented.

We present experimental demonstration of two-qubit entangling operations at speeds comparable to the ions' motional period, significantly faster than the "speed limit" for conventional gate mechanisms.

At these gate speeds, the motional modes are not spectrally isolated, leading to entanglement with both motional modes sensitively depending on the optical phase of the control fields.

[1] J. Garcia-Ripoll *et al.*, Phys. Rev. Lett. 91, **157901** (2003)

[2] L. M. Duan, Phys. Rev. Lett. 93, **100502** (2004)

[3] A. M. Steane *et al.*, New J. Phys. 16, **053049** (2014)

Poster No. 69

Isomer-selective organic chemistry between cations and neutrals under controlled conditions

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Studying gas-phase reactions between molecular ions and neutrals is an important field, providing a better understanding of the chemistry in many environments, such as the interstellar medium. Probing such systems in a controlled environment helps with the understanding of the underlying chemistry. We have developed a new experimental setup for studying reactions between cations and neutrals under controlled conditions utilizing a linear ion trap radially coupled to a TOF-MS.

Current measurements with this setup focus on reactions with small molecules important in basic organic chemistry. We will present results from the reactions between the isomers of C_3H_4 , propyne CH_3CCH and allene CH_2CCH_2 , with $C_2H_2^+$. Measurements show a dependence on the molecular structure and linear chain growth is observed. Furthermore, we will present reaction rates and branching ratios for this fundamental reaction.

Poster No. 70

Micromirror fabrication and characterization for cavity-QED with trapped ions

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We investigate the properties of CO₂ laser ablated micromirrors on fused silica substrates. We discuss the ablation process which was fine-tuned to produce micromirrors of the appropriate size and shape. Cavity finesse is measured as a function of cavity length and mirror geometry. In specific length regimes, correlated with the mirrors' physical radii, we demonstrate excellent laser mode-matching to the cavity's resonator modes. These mirrors and a specially designed surface ion trap form a Fabry-Perot cavity which in combination with a trapped ¹⁷¹Yb⁺ ion will provide a single photon source and greatly increase light collection for state detection in ion trapping experiments.

Poster No. 71

Heisenberg-limited Rabi spectroscopy

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The most precise clocks in the world use narrow optical atomic transitions as frequency references. By quantum-mechanically entangling N such references, the frequency measurement's relative uncertainty can be reduced by $\frac{1}{N}$ factor corresponding to the Heisenberg limit [1], beating the standard quantum limit scaling of $\frac{1}{\sqrt{N}}$. In this work we generate an Ising $\Omega\sigma_x \otimes \sigma_x + J(\sigma_z \otimes I + I \otimes \sigma_z)$ Hamiltonian acting on two trapped ions used as frequency references. We obtain a two-ion correlated Rabi spectrum by scanning the detuning of the laser beams creating the Hamiltonian. This spectrum is twice as narrow as the one given in a single-ion spectroscopy, as expected from the Heisenberg limit. Furthermore, we show that the Ising Hamiltonian acts independently on two separate subspaces of the two-ion system, one spectroscopically sensitive to the mean ion frequency and the second to the difference between ion frequencies.

[1] D. Leibfried *et al*, Science 304, 1476 (2004).

Poster No. 72

Superconducting photon detectors for integration in an ion trap

D. H. Slichter, V. B. Verma, D. Leibfried, R. P. Mirin, S. W. Nam,
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Readout fluorescence photons from trapped ions are traditionally collected with high-numerical-aperture bulk optics and detected with a camera or photomultiplier tube. We report on our efforts to integrate superconducting nanowire single photon detectors (SNSPDs)—a versatile class of fast, high-quantum-efficiency photon counting detectors—into surface electrode ion traps to detect ion fluorescence locally. This architecture can provide scalable, spatially-resolved, high-quantum-efficiency ion state detection.

We demonstrate stand-alone SNSPDs operating at 3.2 K with 76(4) % system detection efficiency (SDE) for 315 nm photons, with a background count rate (BCR) below 1 count per second at saturated detection efficiency. As proof of principle, we fabricate SNSPDs integrated into test ion trap structures and measure their performance at 3.8 K in the presence of realistic rf trapping fields for ${}^9\text{Be}^+$. The presence of rf degrades the maximum SDE of the trap-integrated detector by 9 %, but does not increase the BCR.

*This work funded by IARPA and the NIST Quantum Information Program

Poster No. 73

Characterization of a compact cryogenic package approach to ion trap quantum computing

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Trapped ion-based quantum information processing systems are among the most promising candidates for a scalable qubit platform. One challenge for the expansion of trapped ion systems to a large scale is the lack of repeatable integration technology to realize compact and stable operating environment. In this work, we present a novel ion trapping environment where conventional ultra-high vacuum (UHV) chambers are replaced with a sealed micro-fabricated surface ion trap on a ceramic package operating in a cryogenic environment. Experiments using a cryogenic setup necessitate a new approach to certain tasks when compared to their room temperature equivalents. We use a very low output impedance amplifier driving a resonant LC circuit to generate a sufficiently large radio frequency (RF) voltage. Additionally, the thermal ovens used to generate neutral atoms are replaced by ablation targets. We present the experimental progress towards trapping ions in this compact cryogenic setup.

Progress towards high-fidelity microwave two-qubit gates with trapped ions

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We describe progress towards high-fidelity microwave one and two-qubit gates with trapped ions on a surface trap with integrated microwave electrodes. We highlight improvements from the first generation trap [1] and implementation of our new experimental control system using ARTIQ [2]. Recent experimental results are shown, including tracking motional frequency drifts as well as a new mechanism of spin-motion coupling using low-frequency magnetic-field gradients. This work is supported by IARPA and the NIST quantum information program.

[1] C. Ospelkaus, U. Warring, Y. Colombe, K. R. Brown, J. M. Amini, D. Leibfried, and D. J. Wineland, *Microwave quantum logic gates for trapped ions*, Nature **476**, 181 (2011).

[2] ARTIQ (Advanced Real-Time Infrastructure for Quantum physics), <https://m-labs.hk/artiq/>

Poster No. 75**A single-atom 3D sub-attonewton force sensor**

E. W. Streed¹, V. Blüms¹, M. Piotrowski^{1,2}, M. I. Hussain¹, B. G. Norton¹, S. C. Connell^{1,2}, S. Gensemer^{1,2}, M. Lobino¹

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We demonstrate [1] a three-dimensional sub-attonewton sensitivity force sensor based on super-resolution imaging of the fluorescence from a single laser cooled $^{174}\text{Yb}^+$ ion in a Paul trap. The force is detected by measuring the net ion displacement with nanometer precision, and does not rely on mechanical oscillation. Observed sensitivities were $372 \pm 9_{\text{stat}}$, $347 \pm 12_{\text{sys}} \pm 14_{\text{stat}}$, and $808 \pm 29_{\text{sys}} \pm 42_{\text{stat}}$ zN/ $\sqrt{\text{Hz}}$ in the three dimensions, corresponding to 24x, 87x, and 21x of the quantum limit. We independently verified the accuracy of this apparatus by measuring a light pressure force of 95 zN on the ion, an important systematic effect in any optically based force sensor. This technique can be applied for sensing DC or low frequency forces external to the trap or internally from a co-trapped biomolecule or nanoparticle.

[1] V. Blüms *et al.*, arXiv:1703.06561 [**quant-ph**] (2017)

Qubit decoherence metrology over short timescales

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It is possible to achieve exceptionally long trapped-ion qubit coherence times by using atomic clock transitions, which we implement in $^{43}\text{Ca}^+$ with T_2^* of order a minute. With state preparation and measurement (SPAM) errors typically greater than 10^{-3} , quantum memory performance is usually quantified via Ramsey contrast measurements with delays approaching the coherence time. Information regarding the initial stages of decoherence relevant to quantum computation, where errors remain below 10^{-3} , is then provided by extrapolation of decoherence models only verified at long timescales. We exploit the very small SPAM errors in our qubit to directly investigate the decoherence on timescales much shorter than T_2^* .

Poster No. 77

Development of a photonicallly linked ion trap network

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We report progress towards a networked pair of ion traps, as modules in a scalable quantum network [1]. In our scheme $^{43}\text{Ca}^+$ ions act as logic qubits with $^{88}\text{Sr}^+$ ions as interface qubits and coolant [2].

We present experimental work demonstrating a mixed species ($^{43}\text{Ca}^+ / ^{88}\text{Sr}^+$) entangling gate using only a single pair of Raman beams, as well as entanglement between a $^{88}\text{Sr}^+$ ion and its emitted photon; two key elements required to build a quantum network.

Working towards high fidelity entanglement distribution between nodes, we present details on the design and construction of two network nodes and compact, modular laser systems.

[1] J.I. Cirac *et al.*, Phys. Rev. Lett. 78, **3221** (1997)

[2] R. Nigmatullin *et al.*, New J. Phys. 18, **103028** (2016)

A new closed cycle cryostat system for quantum information experiments with trapped ions

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Cryogenic experiments provide substantial advantages for ion trapping experiments, including longer ion lifetimes, decreased anomalous heating, and the ability to integrate superconducting circuit elements. A closed-cycle system with a mechanical cryocooler does not require frequent refills of liquid helium, and relatively short cool-down and warm-up times allow for quicker trap change-out. Closed cycle systems introduce new challenges - in particular the need for more careful heat load management and decoupling of the trap from mechanical vibrations of the cryocooler. We describe a low-vibration cryostat that addresses these issues, with a base temperature of 3.9K and an rms oscillation amplitude of hundreds of nanometers at the trap. We are currently installing a linear trap to separate ion loading and quantum state manipulation from a zone with an integrated SNSPD detector. Supported by IARPA and the NIST Quantum Information Program.

Poster No. 79

Complete set of transport primitives for scalable quantum computing using trapped ions

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Trapped ions are a promising system for quantum computation. The main challenge is to scale to a large number of qubits. A possible solution is the quantum CCD architecture [1, 2], where smaller groups of ion qubits are split, shuttled around, reconfigured and recombined to perform different tasks such as laser cooling, gate operations, and state detection. Here we demonstrate a complete set of ion string manipulations including transport, rotation, separation of ion crystals in a segmented ion trap with an X-junction. This set of operations is sufficient to generate all necessary operations for the quantum CCD architecture. This work is supported by IARPA and ARO.

- [1] D. J. Wineland *et al.*, J. Res. Natl. Inst. Stand. Technol. **103**, 259 (1998)
- [2] D. Kielpinski *et al.*, Nature **417**, 709 (2002)

The exponential gain of randomness certified by quantum contextuality

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Recently, randomness expansion protocols based on the inequality of the Bell-test and Kochen-Specker (KS) theorem [1], have been demonstrated. These schemes have been theoretically innovated to exponentially expand the randomness and amplify the randomness from weak initial random seed [1]. Here, we demonstrate the protocol of exponential expansion of randomness certified by quantum contextuality, the KCBS inequality in a trapped ion system. In our realization with a $^{138}\text{Ba}^+$ ion, we can exclude the problem of detection loophole and we apply a methods to rule out certain hidden variable models that obey a kind of extended noncontextuality. The scheme can be extended to the protocol of randomness amplification, which requires much more power of 1762 nm laser beam. We also discuss how to amplify the power of the 1762nm laser around 1 W.

[1] S. Pironio, et al., *Nature* **464**, 1021 (2010); M. Um, et al., *Sci. Rep.* **3**, 1627 (2013).

[2] Carl Miller and Yaoyun Shi, arxiv:1411.6608v3 (2015).

Poster No. 81

Single-qubit quantum memory exceeding 10-minute coherence time

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A long-time quantum memory capable of storing and measuring quantum information at the single-qubit level is an essential ingredient for practical quantum computation and communication[1]. Here, we report the observation of over 10-minutes coherence time of a single qubit in a $^{171}\text{Yb}^+$ ion sympathetically cooled by a $^{138}\text{Ba}^+$ ion in the same Paul trap. We also apply a few thousands of dynamical decoupling pulses to suppress ambient noise from magnetic-field fluctuation. The long-time quantum memory of the single trapped ion qubit would be the essential component of scalable quantum computer, quantum networks and quantum money.

- [1] Ladd, T. D. *et al.*, Quantum computers. *Nature* **464**, 45–53 (2010).

Constructing a microwave trapped ion quantum computer

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We present a blueprint for a trapped ion quantum computer. Uniquely, in our approach the number of radiation fields required does not scale with the number of ions present - a single microwave source outside the vacuum system is sufficient. The voltage-controlled location of each ion within a magnetic field gradient is used to provide addressability. By making use of more than two levels in each ion, they can be used for both memory and computation. We introduce a technique to transform all existing two-level quantum control methods to new multi-level quantum control operations that we demonstrate by developing methods to switch a single ion between the two qubit types with infidelities at the 10^{-4} level.

Poster No. 83

Quantum networking with trapped-ion qubits at AFRL

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Quantum networking exploits features of quantum mechanics to provide ultra-secure networks that are both tamper proof and tamper evident. Such networks can be implemented as distant memory nodes connected via photon-based interfaces. Trapped ions are nearly ideal quantum network nodes due to the precise control possible over both the internal and external degrees of freedom, and for their superior performance as long-term quantum memories. Photon-based qubits are the natural choice to transfer information within the network due to the ability to transmit quantum information over long distances and the capability to process information "on-the-fly" between the memory nodes. This poster presents the quantum research being done at AFRL with a focus on trapped ion qubits, the short- and long-term goals of the lab and some of the unique resources we have access to at AFRL.

Rotation sensing with trapped ions

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We present a Sagnac interferometer based on a single trapped ion [1]. The Sagnac phase scales with the enclosed area. State-of-the-art rotation sensing is currently achieved using fiber ring gyroscopes with light circulating many times, increasing the enclosed area. Matter-wave based interferometers have sensitivity enhanced by the ratio of the particle rest energy to the photon energy. Using a single ion we can combine the benefits of high particle energy and many round trips to realise high sensitivity to rotation-induced phases. We will use a modified version of the recently demonstrated laser-induced spin-dependent kicks [2] to entangle the motion and spin of a $^{138}\text{Ba}^+$ ion in a Paul trap and induce macroscopic orbits.

[1] W. C. Campbell and P. Hamilton, *J. Phys. B* **50** (2017) 064002

[2] J. Mizrahi et al., *Phys. Rev. Lett.* **110** (2013) 203001

Poster No. 85

Parallel MEMS fabrication and operation of 3D ion traps

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The devices have a near ideal, three-dimensional electrode geometry and an ion-electrode distance of 240 μm . The structure has 7 operation segments and a loading zone separated by a ~ 0.9 mm transfer segment. High-yield wafer-scale fabrication and automated die-attach processing to the UHV compatible electronic package (doubling as compact feedthrough) is demonstrated. Two batches, each of 2 wafers, achieved 100 % mechanical yield with 85 % of the chips within ± 5 % of the geometric design. RF tests on the first batch showed surface breakdown voltages ranging from 160 V to 600 V amplitude, likely limited by dicing residue. In the second batch, a modified process enabled dicing-free die singulation for improved high-voltage RF performance. Tests on the second batch are in progress and results will be presented. Coherent spectroscopy of a single ion in a room-temperature device shows < 40 quanta/s heating rate at 1 MHz motional frequency. With sideband cooling now operational detailed heating rate studies are in progress.

Towards reduced motional decoherence in ion microtraps

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Experiments with surface ion traps showed that surface contaminants, thought to be sources of electric field noise, can be treated with ion beam sputtering to enable a significant reduction in heating rate. However, this method is not suitable for microtraps with a 3-dimensional electrode geometry. We are developing an alternative method that uses the trap electrodes themselves to generate an *in-situ*, capacitively-coupled, RF microdischarge with strong prospects for selective surface cleaning. We use optical emission spectroscopy to deduce average ion bombardment energies from spectral linewidths. We show that in He and He-N₂ microdischarges, it is possible to realise an average ion bombardment energy above the sputtering threshold for hydrocarbon contaminants, yet well below the threshold for sputtering gold (the electrode material of our devices). This regime can be achieved in a voluminous plasma which fills the aperture of the 3D microstructured trap array.

Poster No. 87

Quantum sensing of oscillating forces without phase control

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In classical systems the stability of a measurement is bound by quantum projection noise accounting for the projective nature of the measurement process. In squeezed state metrology this limitation can be overcome by using non-classical correlations in the noise properties. However, this scheme requires phase control between the squeezing interaction and the interaction realizing the measurement quantity. Here, we demonstrate force detection on a single ion with sensitivities beyond the standard quantum limit by preparing the ion in a motional Fock state. Since Fock states show isotropic behavior in phase space, no phase control between the state preparation and measurement interaction is required. We identify the delocalization of the ion as the main resource for metrological gain and demonstrate quantum enhanced amplitude and phase sensing of a classical force with the same quantum probe.

Quantum logic gates driven by near-field microwaves

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When ions are confined near a waveguide carrying microwave-frequency currents, the resulting magnetic field gradients are strong enough to couple to the ions' motion and hence to implement two-qubit gates [1]. We demonstrate a dynamically-decoupled version of this gate, applied to $^{43}\text{Ca}^+$ "atomic clock" qubits held in a microfabricated room-temperature surface trap, and measure an entangled state fidelity of 99.7(1)% [2]. We are constructing a second generation apparatus including cryogenic cooling [3] and a more advanced trap design incorporating passive field nulling [4].

[1] C. Ospelkaus *et al.*, 2011, DOI: 10.1038/nature10290.

[2] T. P. Harty *et al.*, 2016, DOI: 10.1103/PhysRevLett.117.140501.

[3] J. Labaziewicz *et al.*, 2008,
DOI: 10.1103/PhysRevLett.100.013001.

[4] M. Carsjens *et al.*, 2014, DOI: 10.1007/s00340-013-5689-6.

Poster No. 89

Motional state squeezing and contextuality tests with qutrits on a cryogenic surface-electrode trap

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I will present recent results from the control of both oscillator states and qutrits of trapped $^{40}\text{Ca}^+$ ions. In a cryogenic setup with integrated CMOS switches, we have been working on motional state squeezing using bang-bang control. This has revealed a number of technical imperfections. Meanwhile, as part of an effort to improve $^{40}\text{Ca}^+$ internal state control, we have demonstrated the ability to perform sequences of projective QND measurements on a qutrit, allowing us to observe violations of non-contextual hidden-variable theories. Finally I will present our plans for future traps in the same apparatus, based on standard CMOS fabrication to realize large numbers of electrodes. In particular, I will focus on design of surface trap junctions with constant confinement along the ion-transport channel, which is an alternative approach that might facilitate low-excitation ion-transport across the junction.

Experimental preparation of high NOON states for phonons

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Multi-party entangled states have important applications in quantum metrology and quantum computation. Experimental preparation of large entangled state, in particular, the NOON states, however, remains challenging as the particle number N increases. Here we develop a deterministic method to generate arbitrarily high NOON states for phonons and experimentally create the states up to $N = 9$ in two radial modes of a single trapped $^{171}\text{Yb}^+$ ion. We demonstrate that the fidelities of the NOON states are significantly above the classical limit by measuring the interference contrast and the population through the projective phonon measurement of two motional modes. We also measure the quantum Fisher information of the generated NOON state and observe the Heisenberg scaling in the lower bounds of the phase sensitivity. Our scheme is generic and applicable to other photonic or phononic systems.

Poster No. 91**Multi-species trapped ion system with $^{171}\text{Yb}^+$
and $^{138}\text{Ba}^+$** Junhua Zhang¹, Mark Um¹, Ye Wang¹ and Kihwan Kim¹¹Center for Quantum Information, Institute for Interdisciplinary Information Sciences, Tsinghua University, Beijing, 100084, P. R. China.

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Trapped ion system with more than one species of ions would be essential for a large scaling quantum computer based on either ion-shuttling or photonic connections. Even in a single trap approach for scaling up the system, the multi-species ions can be used for the sympathetic cooling or to probe a quantum information of quantum system composed of one species by the other species. Here we implement an ion trap system with one $^{171}\text{Yb}^+$ ion and one $^{138}\text{Ba}^+$ ion and realize the basic operations of ground state cooling, initializations and detections. For the detection of the $^{138}\text{Ba}^+$ ion, we use the narrow-linewidth laser of 1762 nm to shelve an electronic state in $S_{1/2}$ to the state in $D_{5/2}$. For the quantum operation of $^{171}\text{Yb}^+$ ion and $^{138}\text{Ba}^+$ ion, we apply the Raman laser beams with 355 nm and 532 nm, respectively and demonstrate the entanglement of the two ions through a Mølmer-Sørensen interaction.

Measuring the temperature of barium and ytterbium in mixed species linear chains

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$^{138}\text{Ba}^+$ and $^{171}\text{Yb}^+$ ions are excellent qubit candidates due to unique properties of these species. In one proposal of using mixed species linear chains, Yb^+ is used as the main computational qubit species whereas Ba^+ undergoes cooling; mechanical coupling of Ba and Yb thus provides sympathetic cooling of the latter. However, even the relatively small 25% mass difference between Ba and Yb can cause vibrational mode decoupling that reduces the efficiency of sympathetic cooling. We have performed the equilibrium temperature measurements of linear ion chains formed by two Ba and two Yb ions in different configurations and found results consistent with numerical calculations of the normal mode couplings. The results are discussed and methods to improve Yb cooling are suggested.

Poster No. 93

Verifying Heisenberg's error-disturbance relation using a single trapped ion

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Heisenberg's uncertainty relations have played an essential role in quantum physics since its very beginning. Here we report an experimental test of one of the new Heisenberg's uncertainty relations using a single $^{40}\text{Ca}^+$ ion trapped in a harmonic potential. By two independent methods [1, 2], we verify the uncertainty relation proposed by Busch, Lahti and Werner (BLW) based on a general error tradeoff relation for joint measurements on two compatible observables. The lower bound of the uncertainty, as observed, is satisfied in a state-independent fashion.

[1] Fei Zhou *et al*, *Sci. Adv.* **2**, e1600578 (2016).

[2] Tai-Ping Xiong *et al*, *New J Phys.* **19**, 063032 (2017).

Poster No. 94

Sympathetic sideband cooling of a $^{40}\text{Ca}^+ - ^{27}\text{Al}^+$ pair towards quantum logic clock

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We achieve sympathetic sideband cooling of a $^{40}\text{Ca}^+ - ^{27}\text{Al}^+$ pair. Both axial modes of the two-ion chain are cooled simultaneously to near the ground state of motion. The center of mass mode is cooled to an average phonon number of 0.052(9), and the breathing mode is cooled to 0.035(6). The heating rates of both a single $^{40}\text{Ca}^+$ and the $^{40}\text{Ca}^+ - ^{27}\text{Al}^+$ pair are measured and compared. This may reduce the secular motion time-dilation shift uncertainty in a trap with relative high heating rate using $^{40}\text{Ca}^+$ as auxiliary ion to build $^{27}\text{Al}^+$ optical clock.[1]

[1] J. Shang *et al.*, Chin. Phys. Lett. **33**(10): 103701 (2016)

Excursion

Tuesday, 1630

Two options:

Mesa Hike

- A hike up Kohler Mesa behind NIST which ends at the historic Chautauqua Park.
- Duration: 1.5 hrs
- Length: approx. 2.5 miles (4 km)
- Bring suitable footwear and a drink
- Meeting point: In front of NIST

JILA Lab Tour

- Tour the Lewandowski, Cornell, and Ye labs at JILA
- Sign up sheet available on Monday
- JILA is a 1 mile, 20 min walk away. Transport can be arranged if this presents difficulties.
- Meeting point: In front of NIST

Conference dinner

Wednesday, 1800

The conference dinner will be held in the outdoor plaza of the National Center for Atmospheric Research (NCAR) Mesa Lab. The lab's high-altitude location provides memorable views of the Flatirons and Boulder Valley. The Mesa Lab itself was designed by modernist architect I. M. Pei and completed in 1967. It also featured prominently in Woody Allen's cult classic film 'Sleeper'.

- NCAR Mesa Lab
1850 Table Mesa Drive, Boulder, Colorado, 80305
- Dinner is included for those who registered with catering.
- Buses will be provided to transport you from NIST to the NCAR Mesa Lab at 1800. After the dinner these buses will return you to either NIST, the Courtyard, or the Best Western Inn.

Industry panel

Thursday, 1700

- Jamil Abo-Shaeer
Vice President, Strategic Planning, **AOSense**
- Megan K. Ivory
Quantum Information Systems Team Leader, **ColdQuanta**
- Jungsang Kim
Chief Strategy Officer, **IonQ**

Developing complex AMO lab experiments into commercial products is an exciting new development in our field. We are bringing together three of the leading companies in this area to share their perspectives with the conference. The session will include a chaired panel discussion and an audience Q&A.

Exhibitors and Supporters

<p>In the foyer area Monday - Wednesday</p>

- AOSense, Inc.
- ColdEdge
- ColdQuanta, Inc.
- Covesion, Ltd.
- Harris Corporation
- High Precision Devices, Inc.
- IonQ*
- M-Labs, Ltd.
- M-Squared Lasers, Ltd.
- MOG Laboratories Pty Ltd.
- Montana Instruments Corporation
- NKT Photonics
- ORC, Tampere University of Technology
- Precision Glassblowing
- Princeton Instruments
- Quantel Laser
- Stable Laser Systems
- TOPTICA Photonics AG
- Vescent Photonics
- Zurich Instruments AG

*no exhibit table

Organization

Program Committee

- Andrew Wilson - NIST Boulder - Program Chair
- Heather Lewandowski - JILA/CU Boulder
- Kathy-Anne Soderberg - US Air Force Research Laboratory
- Wes Campbell - UCLA
- Pierre Dubé - National Research Council Canada
- Jeremy Sage - MIT Lincoln Laboratory

Organizing Committee

- David Allcock - NIST Boulder - Organizing Chair
- Andrew Wilson - NIST Boulder
- Raghavendra Srinivas - NIST Boulder
- Gladys Arrisueno - NIST Gaithersburg - Conference Manager
- Karen Startzman - NIST Gaithersburg - Conference Coordinator

Steering Committee

- David Wineland - NIST Boulder
- Rainer Blatt - University of Innsbruck
- Hartmut Häffner - UC Berkeley
- Christopher Monroe - JQI/University of Maryland

Local Support

- Shaun Burd
- Stephen Erickson
- Ben Jeanette
- Katie McCormick
- Anne Reidy
- Crissy Robinson
- Katy Stephenson
- Susanna Todaro
- Terri Viezbicke

17 + NACTI

1st North American Conference on Trapped Ions

	Mon, Aug. 14	Tues, Aug. 15	Wed, Aug. 16	Thu, Aug. 17	Fri, Aug. 18
0900-0930	<i>Welcome & Opening</i>	Fabian Wolf	John Chiaverini	Norbert Linke	Richard Thompson
0930-1000	Samuel Fayer	Kenneth Brown	Matthew Blain	Jungsang Kim	Tomasz Sakrejda
1000-1030	Marianna Safronova	Chin-wen (James) Chou	Kyle McKay	Esteban Martinez	David Hucul
1030-1100	<i>Break</i>	<i>Break</i>	<i>Break</i>	<i>Break</i>	<i>Break</i>
1100-1130	Daniel Gresh	Ania Kwiatkowski	Kunihiro Okada	Murray Barrett	Michael Drewsen
1130-1200	David Hanneke	Christopher Izzo	Neville Coughlan	Geoffrey Barwood	Mark Kokish
1200-1230	Ekkehard Peik	Joseph Tan	Heather Lewandowski	David Hume	Prateek Puri
1230-1400	<i>Lunch</i>	<i>Lunch</i>	<i>Lunch</i>	<i>Lunch</i>	<i>Lunch</i>
1400-1430	Boerge Hemmerling	Tanja Mehlstaeubler	Ian Counts	Jonathan Home	Creston Herold
1430-1500	Paul Hess	Peter Schwindt	Paul Haljan	Peter Maunz	Thomas Harty
1500-1530	Christine Maier	Roland Wester	Phil Richerme	Charles Baldwin	David Allcock
1530-1600	<i>Break</i>	Pavol Jusko	<i>Break</i>	<i>Break</i>	<i>Break</i>
1600-1630	Poster Session 1	<i>Break</i>	Poster Session 2	Isaac Chuang	NIST Lab Tours
1630-1700		JILA Lab Tours or Mesa Hike		Kevin Gilmore	
1700-1730				Industry Panel	
1730-1800					
1800-1830		<i>Conference Dinner at NCAR</i>			
1830-					