^{19}NACTI^{+}

2nd North American Conference on Trapped Ions

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Contents

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13:45–14:15	R. Blatt University of Innsbruck, Austria *Quantum Computation and Quantum Simulation with Strings of Trapped Ca^{+} Ions*
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Talk abstracts

Monday, July 22, 09:30–10:00

Quantum Simulations with Trapped Ions

Chris Monroe[1,2], C. Alderete[1], P. Becker[1], A. Chu[1], K. Collins[1], A. De[1], H. Kaplan[1], A. Kyprianidis[1], N. Linke[1], A. Menon[1], N. Nguyen[1], G. Pagano[1],W. Tan[1], K. Wang[1], and D. Zhu[1]

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Trapped Atomic Ions are the most advanced platform for building quantum computer and simulation systems. Laser-cooled atomic ions hosting atomic clock qubits or effective spins, with essentially no limits on idle coherence time and nearly perfect projective state measurement. Programmable Ising interactions between spins can be implemented through optical forces that modulate the Coulomb interaction, resulting in a long-range interaction graph with tunable range. We present several examples of quantum simulations of interacting spins represented by chains of trapped ions, including the preparation of ground states and phase transitions, dynamics with strongly-interacting spins including observations of prethermal and MBL phases, and Floquet "time crystals." Some of these experiments are pushing the limits of what can be efficiently simulated on classical computers, and may in the future inform exotic behavior of real materials.

Monday, July 22, 10:00–10:30

Quantum Sensing and Simulations with Large Trapped-Ion Crystals*

M. Affolter[1], K. A. Gilmore[1], J. E. Jordan[1], and J. J. Bollinger[1]

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Penning traps provide a platform for quantum simulations and sensing experiments on large arrays of trapped ions. With the use of static electric and magnetic fields, hundreds to thousands of ions can be confined, enabling the formation of large two and three-dimensional ion crystals. This talk will focus on recent experimental upgrades that improve the control and manipulation of single-plane crystals consisting of several hundred Be^+ ions.

For improved sensing and simulation fidelity, electromagnetically induced transparency (EIT) cooling has recently been implemented [**1, 2**]. Substantial sub-Doppler cooling is observed for all the nearly 200 axial drumhead modes with a bandwidth of about 1 MHz. Quantitative measurements of the center-of-mass mode show near ground-state cooling with motional quantum numbers of $\bar{n} = 0.3 \pm 0.2$ obtained within 200 μs. The measured cooling rate is faster than that predicted by single particle theory, consistent with a quantum many-body calculation.

By coupling the spin and motional degrees of freedom of the ions through the application of a spin-dependent optical dipole force, we can measure the temperature of the axial modes, produce long-range Ising interactions, and sense displacements of the ion crystal that are small compared to the ground state zero-point fluctuations [**3**]. Recent phase stabilization of this optical dipole force at the ions has enabled an order-of-magnitude improvement in the sensing of small displacements. This enables the detection of weak electric fields with a projected sensitivity of $< 10\, nV/m/\sqrt{Hz}$ on resonance with the center-of-mass mode, and may provide an opportunity to place limits on dark matter couplings due to particles such as axions and hidden photons that couple to ordinary matter through weak electric fields.

*In collaboration with A. Shankar, R. J. Lewis-Swan, A. Safavi-Naini, M. Holland, and A. M. Rey.

[1] J. E. Jordan *et al.*, Phys. Rev. Lett. **122**, 053603 (2019)
[2] A. Shankar *et al.*, Phys. Rev. A **99**, 023409 (2019)
[3] K. A. Gilmore *et al.*, Phys. Rev. Lett. **118**, 263602 (2017)

Monday, July 22, 11:15–11:45

Improved Test of Local Lorentz Invariance from a Deterministic Preparation of Entangled States

E. Megidish[1], J. Broz[1], N. Greene[1], S. Mouradian[1], W. T. Chen[1], and H. Häffner[1]

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The high degree of control available over individual atoms enables precision tests of fundamental physical concepts. In this talk I would present our recent study showing how precision measurements can be improved by preparing entangled states immune to the dominant source of decoherence [**1**]. Using $^{40}Ca^{+}$ ions, we explicitly demonstrate the advantage from entanglement on a precision test of local Lorentz invariance for the electron. Reaching the quantum projection noise limit set by quantum mechanics, we observe, for bipartite entangled states, the expected gain of a factor of two in the precision. Under specific conditions, multipartite entangled states may yield substantial further improvements.

In the second part of the talk I will describe the design of our new experimental platform based on Sandia's HOA surface trap. The new platform includes High NA single ion addressing, in situ Argon ion milling and fast shutteling of ions. These features would enable scaling up the number of ions and perfrom high fidelity single-qubit and two-qubit gates.

[1] E. Megidish *et al.*, Phys. Rev. Lett. **122**, 123605 (2019)

Monday, July 22, 11:45–12:15

Quantum simulation of spin models in arbitrary spatial dimensions using a linear chain of ions

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Trapped ions are among the most advanced technology platforms for quantum simulation of spin models, due to their long coherence time, high fidelity initialization and detection of individual spins, and the ability to simulate various types of Hamiltonians. However, ions are most readily trapped as a linear chain in radio-frequency traps, limiting their use to simulate higher dimensional quantum systems. In this talk, I'll describe an analog and an analog-digital hybrid [**1**] quantum simulation protocols to simulate programmable 2D and 3D spin models in a linear ion chain, by manipulating phonon-mediated long-ranged interactions between ion spins. The analog simulation protocol employs machine learning methods to optimize all individual spin-phonon couplings to realize the target spin-spin interaction graph of higher dimensional lattices. The hybrid protocol relies on dynamical control of global spin-phonon couplings, for example by using global laser beams, and scales efficiently with the system size. The ability to dynamically engineer lattice geometries enables the investigation of a rich variety of physical phenomena such as spin frustration, topological states, and quantum quenches. I'll also introduce 'QuantumIon', an open-access multi-user quantum computer that we are building at University of Waterloo.

[1] F. Rajabi *et al.*, *npj Quantum Information* **5:32** (2019)

Monday, July 22, 13:45–14:15

Quantum optomechanics with trapped ions and nanospheres

D. S. Bykov[1], L. Dania[1], M. Knoll[1], P. Mestres[1], L. Schmöger[1,2], L. Neumeier[3], D. E. Chang[3,4], and T. E. Northup[1]

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The motional degrees of freedom of ions in linear Paul traps enable the entangling gate operations at the heart of quantum computing applications. Here, we consider motion in an ion trap in a different context, namely, in the setting of optomechanics.

First, we examine a single ion as an optomechanical oscillator coupled to the field of an optical cavity, in which a mechanical displacement of the ion shifts the cavity resonance frequency. With this system, considering current experimental parameters, it should be possible to observe the intrinsically nonlinear interaction between single phonons and single photons, a regime known as optomechanical strong coupling that has not yet been accessed experimentally. Measurements of photon statistics are proposed, and a signature of optomechanically induced photon blockade is predicted [**1**].

Next, we consider a system in which the center-of-mass motion of a silica nanoparticle is coupled to an optical cavity. Paul traps provide one means to levitate such a particle, and the advantages of ion traps will be discussed for experiments that aim to bring the particle's motion into the quantum regime. We demonstrate techniques for loading and charging nanoparticles in a Paul trap under ultra-high vacuum [**2**], and we observe cooling of the particle's secular motion via electrical and optical feedback. An experimental system will be presented in which we plan to couple both the center-of-mass motion of the nanoparticle and the $3^2D_{5/2} - 4^2P_{3/2}$ dipole transition of a single Ca^+ ion to an optical cavity. This system offers prospects for new cooling schemes in the unresolved sideband regime and for nonclassical motional state preparation.

[1] L. Neumeier, T. E. Northup, and D. E. Chang, Phys. Rev. A **97**, 063857 (2018)

[2] D. S. Bykov, P. Mestres, L. Dania, L. Schmöger, and T. E. Northup, arXiv:1905.04204 (2019)

Monday, July 22, 14:15–14:45

Hybrid trapped ion and neutral atom based quantum networking

Qudsia Sara Quraishi[1,2], John Hannagen[2], and James D. Siverns[2]

[1]Army Research Laboratory, Adelphi, MD 20783 [2]Joint Quantum Insitute, University of Maryland, College Park, MD 20742

Hybrid quantum networking between disparate systems is of increasing interest in distributed quantum information. Trapped ions are strong candidates for communication nodes and as quantum memories, possessing high fidelity ion-photon entanglement, high quantum gate fidelities and long coherence times. Neutral-atom based quantum nodes also have a wide range of applications including in quantum simulation, metrology and for quantum storage. A photonic link between these systems would provide an interesting platform from which to build a quantum network. Here, we report on a series of experiments enabling a hybrid ion-neutral-based remotely connected quantum networking platform. To spectrally match the photons produced by the two systems, we use quantum frequency conversion to convert the optical frequency of the photons produced by the trapped ion to match those from the neutral atom source. First, we show conversion of 493 nm photons, emitted by a 138Ba+ ion, to a wavelength near 780 nm, whilst preserving their quantum statistics[**1**]. Secondly, we link the photons derived from the ion to the neutral atom system via slow light implemented in a warm 87Rb vapor[**2**]. We observe tunable delays up to 13.5 ns and note that the photon's temporal profile is preserved. Finally, we report on Hong-OuMandel interference between on-demand photons produced by a trapped ion and those produced by a neutral-atom Rydberg ensemble, located in adjacent building and linked via a 150 m optical fiber. The photons are optically and temporally synchronized via another pair of optical fibers for heterodyne optical beatnote stabilization and for triggering TTL control, respectively. We give projected rates for ion-Rydberg photonic-based entanglement. These results are the first to show a photonic link between photons from the trapped ion and neutral atom

[1] J. D. Siverns, J. Hannegan, Q. Quraishi, Phys. Rev. Applied 11, 014044, (2019).
[2] J. D. Siverns, J. Hannegan, Q. Quraishi, arXiv:1808.07928 (2018).

Monday, July 22, 14:45–15:15

Quantum Networking with Trapped-Ion Qubits at AFRL

K-A Brickman Soderberg[1], N. Amidon[1,2], P. Haas[1,3], D. Hucul[1], Lt K. Poole[1], H. Rutbeck-Goldman[1,4], B. Tabakov[1], Lt J. Williams[1], and Lt N. Woodford[1]

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[4]Griffiss Institute, Rome, NY, 13441

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 talk 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.

Tuesday, July 23, 09:00–09:30

Search for Lorentz symmetry violation with trapped ions

Marianna Safronova[1,2]

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Questioning basic assumptions about the structure of space and time has greatly enhanced our understanding of nature. Modern tests of Einstein's theory of relativity try to measure so-far-undetected violations of Lorentz symmetry; accurately comparing the frequencies of optical clocks is a promising route to further improving such tests. PTB experiment [**1**] demonstrated agreement between two single-ion optical clocks at the 10^{-18} level, directly validating their uncertainty budgets, over a six-month comparison period. The ytterbium ions of the two clocks were confined in separate ion traps with quantization axes aligned along non-parallel directions. Hypothetical Lorentz symmetry violations would lead to periodic modulations of the frequency offset as the Earth rotates and orbits the Sun. From the absence of such modulations at the 10^{-19} level a stringent limits of the order of 10^{-21} on Lorentz symmetry violation (LV) parameters for electrons was deduced, improving previous limits by two orders of magnitude.

A broadly applicable new method to search for the violation of local Lorentz invariance with atomic systems [**2**] will also be discussed. The new scheme uses dynamic decoupling and can be implemented in current atomic clock experiments to improve the precision of LV searches by several orders of magnitude. Moreover, the scheme can be performed on systems with no optical transitions, and therefore it is also applicable to highly charged ions which exhibit a particularly high sensitivity to Lorentz invariance violation.

[1] Ch. Sanner, N. Huntemann, R. Lange, Ch. Tamm, E. Peik, M. S. Safronova, S. G. Porsev, Nature **567**, 204 (2019).
[2] R. Shaniv, R. Ozeri, M. S. Safronova, S. G. Porsev, V. A. Dzuba, V. V. Flambaum and H. Häffner, Phys. Rev. Lett. **120**, 103202 (2018).

Tuesday, July 23, 09:30–10:00

The nuclear clock: Recent progress and perspectives

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[1] Ludwig-Maximilians-University Munich, 85748 Garching, Germany

A nuclear optical clock based on a single ^{229}Th ion is expected to achieve a higher accuracy than the best atomic clocks operational today [**1**]. Although already proposed back in 2003 [**2**], this nuclear clock has not yet become reality. The main obstacle that has so far hindered the development of a nuclear clock was an unprecise knowledge of the energy value of a nuclear excited state of the ^{229}Th nucleus, generally known as the ^{229}Th isomer. This metastable nuclear excited state is the one of lowest energy in whole nuclear landscape and - with an energy of less than 10 eV - allows for direct nuclear laser excitation, which poses a central requirement for the development of a nuclear clock.

In the past few years significant progress toward the development of a nuclear clock has been made: Starting with a first direct detection of the ^{229}Th isomer in 2016 based on its internal conversion decay channel [**1**], the isomeric lifetime could be determined in 2017 [**5**], followed by a first laser-spectroscopic characterization in 2018 [**6**]. Most recently a first energy determination based on the isomer's direct detection was successful [**7**], thereby constraining the isomeric energy value to sufficient precision to determine the laser technology required in the nuclear clock concept and paving the way for first nuclear laser spectroscopy experiments [**2**].

In the presentation I will give an overview over the current status of the nuclear clock development, with a particular focus on the most recent progress. Also the next required steps will be detailed and future perspectives will be given.

[1] C.J. Campbell et al., Phys. Rev. Lett. 108, 120802 (2012).
[2] E. Peik, C. Tamm, Eur. Phys. Lett. 61, 181 (2003).
[3] L. von der Wense et al., Nature 533, 47 (2016).
[4] B. Seiferle et al., Phys. Rev. Lett. 118, 042501 (2017).
[5] J. Thielking et al., Nature 556, 321 (2018).
[6] B. Seiferle et al., submitted to Nature, arXiv:1905.06308 (2019).
[7] L. von der Wense et al., submitted to PRA, arXiv:1905.08060 (2019).

Tuesday, July 23, 10:00–10:30

Quantum Logic Spectroscopy of Cold Highly Charged Ions

S. A. King[1], T. Leopold[1], P. Micke[1,2], L. J. Spieß[1], E. Benkler[3],
J. R. Crespo López-Urrutia[2], and P. O. Schmidt[1,4]

[1]QUEST Institute, Physikalisch-Technische Bundesanstalt, Braunschweig, Germany
[2]Max-Planck-Institut für Kernphysik, Heidelberg, Germany
[3]Physikalisch-Technische Bundesanstalt, Braunschweig, Germany
[4]Institut für Quantenoptik, Leibniz Universität Hannover, Hannover, Germany

The extreme properties of highly charged ions (HCIs) make them favourable for tests of fundamental physics as well as for use as next-generation optical frequency standards [**1**]. However, megakelvin-level plasma temperatures and strong systematic perturbations inherent to their production and storage has thus far limited spectroscopic accuracy to little better than the part-per-million level [**2**], more than eleven orders of magnitude behind state-of-the-art optical clock experiments.
We have developed techniques to extract HCIs (in this case Ar^{13+}) from a compact electron beam ion trap (EBIT) [**1**], decelerate them [**5**], and capture them in a cryogenic linear Paul trap [**6**] where they are sympathetically cooled to the ground state of motion using a single laser-cooled Be^{+} ion. The final equivalent HCI temperature is around 10^{-4} K in these modes, ten orders of magnitude lower than their temperature in the EBIT. We have coherently excited the ${}^2P_{1/2} \rightarrow {}^2P_{3/2}$ magnetic-dipole (M1) clock

transition in the Ar^{13+} ion using an ultrastable laser at 441 nm, with quantum logic operations [**7**] enabling us to transfer the internal state of the HCI to the Be^{+} ion. The decahertz-level transition linewidths observed so far are primarily limited by the short 9.6 ms lifetime of the excited electronic state, but nevertheless allow us to resolve relativistic, interelectronic interaction and QED corrections to the g-factor of the $^2P_{3/2}$ state for the first time.
This work paves the way for a 10^9 to 10^{13}-fold improvement in spectroscopic resolution on an enormous variety of interesting species, and demonstrates the feasibility of an optical clock based on HCI.

[1] M. G. Kozlov *et al.*, Rev. Mod. Phys. **90**, 045005 (2018)
[2] I. Draganić *et al.*, Phys. Rev. Lett. **91** 183001 (2003)
[3] P. Micke *et al.*, Rev. Sci. Inst. **89** 063109 (2018)
[4] L. Schmöger *et al.*, Science **347** 1233–1236 (2015)
[5] T. Leopold *et al.*, arXiv:1901.03082 (2019)
[6] P. O. Schmidt *et al.*, Science **309** 749 (2005)

Tuesday, July 23, 11:15–11:45

Trapped ion atomic clock development for space and ultra-stable ground applications

E. A. Burt[1], L. Yi[1], R. L. Tjoelker[1], and J. D. Prestage[1]

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For many years the Jet Propulsion Laboratory at Caltech has been engaged in research on the use of trapped ions in atomic clocks, with a special emphasis on clocks that have the ability to run continuously and autonomously. Starting with the linear quadrupole rf trap and progressing to the linear multi-pole trap and finally to the compensated linear multi-pole trap it was quickly realized that clocks using this technology could also be quite stable, with the latter demonstrating UTC(k)-like stability in a single clock. Work has also progressed in the direction of making these clocks smaller and more amenable to operation in space without sacrificing performance. This space clock work has culminated with the recent launch of a trapped ion atomic clock as part of the NASA's Deep Space Atomic Clock (DSAC) Technology Demonstration Mission – the first use of trapped ion technology in space.

In this talk I will discuss both JPL's work on stable ground-based clocks and the DSAC clock as well as applications for both. For the ground-based clock these range from characterizing other clocks, to basic science as part of the European Space Agency Atomic Clock Ensemble in Space (ACES) project. For DSAC applications range from enabling a new paradigm in space navigation to planetary atmospheric and gravitational science.

Tuesday, July 23, 11:45–12:15

Systematic uncertainty and correlation spectroscopy of the NIST ^{27}Al^{+} quantum-logic clocks

S. M. Brewer[1,2], J.-S. Chen[1,2], E. R. Clements[1,2], M. E. Kim[1,2], A. M. Hankin[1,2], K. Cui[1], C. W. Chou[1], D. J. Wineland[1,2,3], D. B. Hume[1], D. R. Leibrandt[1,2]

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A single ion clock based on quantum-logic spectroscopy of the $^1S_0 \longleftrightarrow {}^3P_0$ transition in ^{27}Al$^+$ has been evaluated at NIST to have a systematic uncertainty of 9.4×10^{-19} and a frequency stability of $1.2 \times 10^{-15}/\sqrt{\tau}$ [**1**]. A ^{25}Mg$^+$ ion is simultaneously trapped with the ^{27}Al$^+$ ion and used for sympathetic cooling and state readout. Improvements in a new trap have led to reduced secular motion heating, compared to previous ^{27}Al$^+$ clocks, enabling clock operation with ion secular motion near the three-dimensional ground state. Operating the clock with a lower trap drive frequency has reduced excess micromotion compared to previous ^{27}Al$^+$ clocks. Both of these improvements have led to a reduced time-dilation shift uncertainty. Other systematic uncertainties including those due to blackbody radiation and the second-order Zeeman effect have also been reduced.

A comparison between highly accurate clocks, which is necessary to evaluate and verify their accuracy, requires commensurate measurement precision. While the atomic systems used as clocks have long coherence times, noise from the local oscillator often limits the measurement stability. One way to overcome this limitation is by performing correlation spectroscopy, in which a Ramsey pulse sequence derived from the same probe laser is applied to both clocks synchronously [**2**]. Such coherent differential phase measurements between two atomic systems permit interrogation times beyond the laser coherence time. We report on the demonstration of correlation spectroscopy between two independent $^{27}Al^{+}$ quantum-logic clocks separated by 7 m. By removing the limitation set by the coherence time of the local oscillator, we extend the interrogation time of the two single ion clocks from 150 ms to several seconds. The corresponding reduction in quantum projection noise limit results in a frequency comparison instability significantly lower than is currently possible for incoherent comparisons using the same local oscillator.

This work was supported by NIST, DARPA, and ONR. S.M.B. was supported by ARO through MURI grant W911NF-11-1-0400.

[1] S. M. Brewer *et al.*, arXiv:1902.07367 (2019)
[2] C. W. Chou *et al.* Phys. Rev. Lett. **106**, 160801 (2011)

Tuesday, July 23, 13:45–14:15

Quantum Computation and Quantum Simulation with Strings of Trapped Ca^+ Ions

Rainer Blatt[1,2]

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The state-of-the-art of the Innsbruck trapped-ion quantum computer is briefly reviewed. We present an overview on the available quantum toolbox and discuss the scalability of the approach. Fidelities of quantum gate operations are evaluated and optimized by means of cyclebenchmarking[**1**] and we show the generation of a 16-qubit GHZ state. Entangled states of a fully controlled 20-ion string are investigated[**2**] and used for quantum simulations.

In the second part, we present both the digital quantum simulation and a hybrid quantumclassical simulation of the Lattice Schwinger model, a gauge theory of 1D quantum electrodynamics. Employing universal quantum computations, we investigate the dynamics of the pair-creation[**1**] and using a hybrid-classical ansatz, we determine steady-state properties of the Hamiltonian. Hybrid classical-quantum algorithms aim at solving optimization problems variationally, using a feedback loop between a classical computer and a quantum co-processor, while benefitting from quantum resources[**5**].

[1] A. Erhard et al., arXiv:1902.08543 (2019)
[2] N. Friis et al., Phys Rev X. 8 021012 (2018)
[3] E. A. Martinez et al., Nature 534, 516 (2016)
[4] C. Kokail et al., Nature 569, 355–360 (2019)

Tuesday, July 23, 14:15–14:45

Probing quantum properties in atom-ion collisions experiments

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I will review our recent experiments that look for quantum features in atom-ion collisions. In our hybrid system, we overlap ground-state cooled $^{88}Sr^{+}$ ion with ultra-cold ^{87}Rb atoms. For this mixture the unfavorable mass ratio prohibits reaching equilibrium temperature of the S-wave regime, nevertheless quantum phenomena still underlie many of the observed results. One example is the weak dependence in the partial wave of spin-exchange atom-ion collisions, which results in a cross section that does not follow the semi-classical approximation despite occurring at energies that involve many partial waves. Another is the process of electronic excitation-exchange through Landau-Zener avoided crossings which leads to a loss of total electronic angular-momentum to external degrees of freedom. I will further discuss our effort to observe shape resonance in atom ion collisions. Here the cross section of inelastic process is expected to exhibit large dependence on the collision energy due to the formation of atom-ion molecular quasi bound states.

Tuesday, July 23, 14:45–15:15

Trapped Ion Quantum Computing

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I describe the approach of trapped ion qubits for quantum computing. In Mainz we follow the seminal proposal by David Wineland for a scalable architecture [**1**], which requires trap technologies and fabrication methods, control electronics for quantum register reconfigurations [**1**], but also the improvements qubit coherence [**2**], and its characterization [**1**]. We have realized multi-qubit operations [**5**], eventually leading to quantum error correction algorithms [**6**]. I conclude reporting on a novel fast entanglement operation just by applying electric displacement pulses shuttling Rydberg ion crystals [**7**].

[1] D. Kielpinski, C. Monroe, D. J. Wineland, "Architecture for a large-scale ion-trap quantum computer", Nature **417**, 709 (2002)

[2] H. Kaufmann, et al., "Fast ion swapping for quantum information processing", Phys. Rev. A **95**, 052319 (2016)

[3] T. Ruster et al. "A long-lived Zeeman trapped-ion qubit", Applied Physics B, **122**, 1 (2016)

[4] T. Ruster, et al. "Entanglement-Based dc Magnetometry with Separated Ions", Phys. Rev. X **7**, 031050 (2017)

[5] H. Kaufmann et al "Scalable Creation of Long-Lived Multipartite Entanglement", Phys. Rev. Lett. **119**, 150503 (2017)

[6] A. Bermudez et al., "Assessing the Progress of Trapped-Ion Processors Towards Fault-Tolerant Quantum Computation", Phys. Rev. X **7**, 041061 (2017)

[7] J. Vogel, W.Li, A. Mokhberi, I. Lesanowsky, F. Schmidt-Kaler, "Shuttling of Rydberg ions for fast entangling operations", arXiv:1905.05111 (2019)

Wednesday, July 24, 09:00–09:30

High-rate, high-fidelity entanglement across an elementary quantum network

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We have recently demonstrated remote entanglement of qubits across a two-node quantum network, with significantly higher fidelity and rate than previously achieved using trapped ions. I will report latest results, and progress towards more complex algorithms such as entanglement distillation.

Wednesday, July 24, 09:30–10:00

Quantum Control of Atomic and Molecular Ions at NIST

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The basic requirements for quantum computing and quantum simulation have been demonstrated in separate experiments on trapped ions. Construction of a large-scale information processor will require synthesis of these elements and implementation of high-fidelity operations on a very large number of qubits. As in other quantum computing implementations, this is still well in the future. In proof-of-principle experiments, NIST and other groups are addressing part of the scaling issue by demonstrating simple quantum processing protocols incorporating different ion species in multi-zone arrays of traps and integrating elements of classical control and readout in the trap structure. Producing and controlling many copies of these basic building blocks would allow highly parallel and scalable processing. In the near term, some simple quantum algorithms are being used to aid in quantum control and quantum metrology, such as in atomic clocks and precision manipulation and spectroscopy of single molecular ions.

We have implemented a teleported controlled-NOT gate in a dual species experiment featuring the majority of elements required for scalable quantum information processing. We characterize the teleported gate operation by informationally complete quantum process tomography [**1**]. Ongoing experiments towards entangling operations [**2, 3**] and motional squeezing entirely based on microwave and radio-frequency magnetic fields in miniaturized surface traps will be discussed [**4**]. By combining techniques from quantum logic ion clocks with far-detuned Raman-transitions driven by a continuous laser or a frequency-comb, we can initialize and coherently manipulate pure quantum states of molecular ions in ways that are generally applicable to a wide range of species in the same experimental setup. We demonstrate this approach by performing sub-kHz-precision spectroscopy and coherent manipulation of pure rotational quantum states of ^{40}CaH$^+$ [**5**] and by entangling a qubit composed of the internal states of a ^{40}Ca$^+$ ion with the rotational quantum state of the ^{40}CaH$^+$ molecule.

[1] Y. Wan *et al.*, arXiv:1902.02891 (2019).
[2] R. T. Sutherland *et al.*, New J. Phys. **21** 033033 (2019).
[3] R. Srinivas *et al.*, Phys. Rev Lett bf 122, 163201 (2019).
[4] S. C. Burd *et al.*, arXiv:1812.01812 (2018).
[5] C. W. Chou *et al.*, Nature **545**, 203 (2017).

Wednesday, July 24, 10:00–10:30

Mixed-species and integrated platforms for trapped-ion QIP

K.K. Mehta[1], C. Zhang[1], M. Malinowski[1], T.-L. Nguyen[1], B. Macdonald-de Neeve[1], M. Marinelli[1], V. Negnevitsky[1], C. Flühmann[1], F. Lancelotti[1], T. Behrle[1], M. Stadler[1], and J.P. Home[1]

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Practical and useful QIP will require significant jumps in robustness and error rates of basic operations, as well as in scale and integration. I will describe ongoing work which aims to address multiple limitations of earlier experiments [**1**] with regards to scaling and complexity. Integration of optical components into traps promises reduced drifts, stable tight focusing, and extensibility. We are currently operating planar ion traps at low temperature with integrated silicon nitride photonics. Building on previous work [**2**] our designs aim to implement multi-qubit operations with $^{40}Ca^{+}$ ions in devices allowing low (2 dB measured) fiber-waveguide coupling losses at 729 nm on multiple channels. To counter experimental drifts, we have devised fast calibration and feedback techniques for efficiently maintaining operation fidelities. This includes real-time Bayesian methods for calibrating detunings and amplitudes in 2-qubit MS gates while minimizing required resources. Finally, I will summarize our ongoing work with low-excitation splitting and joining of $^{9}Be^{+}$ and $^{40}Ca^{+}$ mixed-species crystals, as are required for realizing more complex circuits in a QCCD architecture [**3**]

[1] V. Negnevitsky, M. Marinelli *et al.*, Nature 563, 527-531 (2018).
[2] K. Mehta *et al.*, Nature Nanotechnology 11, 1066-1070 (2016).
[3] D. Kielpinski *et al.*, Nature 417, 709-711 (2003).

Wednesday, July 24, 11:15–11:45

Myth: SPAM is either a versatile canned meat product or unsolicited email

W. C. Campbell[1,2], J. E. Christensen[1], T. Dellaert[1], D. Hucul[1,3], E. R. Hudson[1,2], A. Ransford[1], C. Roman[1]

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The development of quantum technologies has followed from our ability to create and isolate pure quantum states in experimental systems. The power to faithfully prepare and read out single quantum states lies at the heart of this development effort, and we will discuss work aimed at improvements in both the speed and fidelity of state preparation and measurement (SPAM) of trapped ion qubits. New types of qubits will also be discussed in the context of the role they can play in science and the effort to scale up trapped ion systems. Along the way, some myths might get busted.

Wednesday, July 24, 11:45–12:15

Progress toward nonbinary quantum logic in barium ions

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I will describe my group's progress toward developing high-fidelity implementation of a universal set of operations on trapped ion qudits (i.e., multi-level generalizations of qubits). We have described protocols for measurement, single-qudit gates, and two-qudit entangling gates, which are generalizable to different qudit dimensions. We show numerically that for three-level qudits encoded in barium hyperfine states, our protocols can exceed 99% fidelity, accounting for known experimental imperfections in qubit operations. In our scheme, measurements of the qudit states are accomplished using frequency-resolved transitions to a metastable $D_{5/2}$ manifold, along with state-dependent fluorescence collection, in a manner that allows for discriminating among all possible qudit states. Single-qudit gates and two qudit gates can be performed using far-detuned lasers to drive stimulated Raman transitions. We show that the concepts of the 'Mølmer-Sørensen' interaction, in which optical dipole forces are used to modulate the Coulomb interaction among ions in a state-dependent fashion, can be extended to multi-level qudits with low intrinsic error rates. This set of tools will be suitable for quantum computing applications, along with quantum simulations of integer spins. In addition to discussing qudit operations, I will briefly present the architecture design for QuantumIon, an open-access quantum computing facility being constructed at Waterloo.

Thursday, July 25, 09:00–09:30

Progress in the quantum control of single molecular ions

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The development of methods for the coherent manipulation of single isolated molecules has made rapid progress in recent years [**1, 2**] and has become a new frontier in AMO and quantum physics. An exciting application of these techniques are precision spectroscopic measurements on single molecules which will allow for tests of fundamental theories beyond the standard model, for the development of mid-IR atomic clocks based on molecular vibrational transitions, for the observation and control of chemical reactions on the single-particle level, and for the precise benchmarking of molecular-structure theory.

In our experiments [**3**], a molecular beam is overlapped with a radio-frequency ion trap. Single nitrogen (N_2) molecules from the molecular beam are prepared in a specific rotational-vibrational ionic state using resonance-enhanced multi-photon ionization [**4**]. Subsequently, the molecular ions are sympathetically cooled by single atomic ion to their common motional ground state. State-selective coherent motional excitation [**3, 5, 6**] is used as a quantum non-demolition method to detect the molecular state via the co-trapped atomic ion. Narrow quantum-cascade lasers are developed to preform precision spectroscopy on a narrow dipole-forbidden vibrational transition at 65 THz [**7**] and to utilize projective state preparation. We use N_2^+ as a prototype molecule particularly suited to precision measurements because it features narrow electric-dipole forbidden vibrational transitions in the electronic ground state. Nevertheless, our methods can be extended to a general class of diatomic and polyatomic molecules.

In this talk, I will present a detailed characterization of our method and discuss further developments and applications.

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

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

[3] Z. Meir, G. Hegi, K. Najafian, M. Sinhal and S. Willitsch, *Faraday Discussions* (2019). DOI: 10.1039/C8FD00195B

[4] X. Tong, A. H. Winney and S. Willitsch, *Phys. Rev. Lett.* **105**, 143001 (2010).

[5] J. C. J. Koelemeij, B. Roth and S. Schiller, *Phys. Rev. A* **76**, 023413 (2007).

[6] D. Hume *et al.*, *Phys. Rev. Lett.* **107**, 243902 (2011).

[7] M. Germann, X. Tong and S. Willitsch, *Nat. Phys.* **10**, 820 (2014).

Thursday, July 25, 09:30–10:00

Dipolar and Dipole-Phonon Quantum Logic with Sympathetically Cooled Molecular Ions

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We discuss new ideas for quantum logic using both dipolar and dipole-phonon interactions between sympathetically cooled molecular ions [**1**]. These protocols provide potentially attractive and scalable means for entangling molecular ions, as well as non-destructive readout of their internal states. Additionally, we report on recent developments to understand, and even control, low-temperature atom-ion collisions necessary for producing and using these molelcular ions for quantum logic. Specifically, we discuss the observation of reaction blockading in excited-state atom-ion reactions at low temperatures [**2**]. Reactive excited-state collisions between $\mathrm{Ca}(^1\mathrm{P}_1)$ and BaCl^+ are dramatically suppressed at low collision energy, where the collision process takes more time than the spontaneous emission lifetime of the excited state. In further studies of collisions between $\mathrm{Ca}(^1\mathrm{P}_1)$ and $\mathrm{Yb}^+(^2\mathrm{S}_{1/2})$, we again observe reaction blockading at low temperatures and demonstrate control over this effect with the addition of a catalyst laser [**3, 4**]. In this way, we engineer

excited-state atom-ion interactions at low temperatures, allowing us to effectively turn these reactions on or off with the catalyst laser. Finally, we introduce a method to control the collision energy of atom-ion interactions by shuttling ions through a magneto-optical trap [**5**]. In this way, we achieve a high collision energy resolution compared to a thermal distribution as well as a large range of tunability from 0.05 to 100 K.

[1] E. R. Hudson and W. C. Campbell, Phys. Rev. A, **98**, 040302(R) (2018)
[2] P. Puri, M. Mills, I. Simbotin, J. A. Montgomery, R. Côté, C. Schneider, A. G. Suits, and E. R. Hudson, Nat. Chem. (2019)
[3] M. Mills, P. Puri, M. Li, S. J. Schowalter, A. Dunning, C. Schneider, S. Kotochigova, and E. R. Hudson, Phys. Rev. Lett. (2019)
[4] M. Li, M. Mills, P. Puri, A. Petrov, E. R. Hudson, and S. Kotochigova, Phys. Rev. A (2019)
[5] P. Puri, M. Mills, E. P. West, C. Schneider, and E. R. Hudson, Rev. Sci. Instrum. **89**, 083112 (2018)

Thursday, July 25, 10:00–10:30

Molecular Ion State Control and Prospects for Precision Measurement

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Obtaining control over the rotational and vibrational quantum state is a prerequisite for many applications of trapped molecular ions. I will discuss extension of a broadband optical pumping technique to allow preparation of arbitrary rotational states of certain trapped molecular ions. The technique has been demonstrated to prepare trapped SiO^+ into highly excited *super-rotor* states with narrow rotational distributions. I will also discuss prospects for measurement of time-varying fundamental constants using a single polar molecular ion.

Thursday, July 25, 11:15–11:45

Towards sympathetic translational and rotational cooling of CaH^+ in an ion-atom hybrid trap

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Hybrid ion-atom traps are an ideal system for studying rich chemical interactions between cold atoms and ions. These traps are also a good platform to achieve translationally and internally cold molecular ions [**1**]. To facilitate these experiments, we have developed an apparatus incorporating a spatially overlapped potassium (K) magneto-optical trap (MOT) and a calcium (Ca^+) ion trap. The laser-cooled atomic ions can efficiently cool the translational degrees of freedom of the molecular ions and the internal states of the molecule can be sympathetic cooled using the laser-cooled atoms. Our ion- atom hybrid apparatus is integrated with a high-resolution time-of-flight mass spectrometer for the identification of any reaction products [**2**]. We present our initial experimental results on charge exchange interaction between cold K and Ca^+. We describe our plans for using rovibronic spectroscopy of CaH^+ [**3**] to measure the rotational cooling of CaH^+ by the K MOT.

[1] E. R. Hudson, Phys. Rev. A **79**, 032716 (2009)
[2] C. Schneider *et al.*, Phys. Rev. Applied **2**, 034013 (2014)

[3] A. T. Calvin *et al.*, The Journal of Physical Chemistry A. **122**, 3177 (2018)

Thursday, July 25, 11:45–12:15

A precision measurement of the electron's Electric Dipole Moment using trapped molecular ions

Y. Zhou[1], K. B. Ng[1], W. B. Cairncross[1], T. S. Roussy[1], T. Grogan[1], Y. Shagam[1], A. Vigil[1], M. Pettine[1], J. Ye[1], and E. A. Cornell[1]

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Precision measurements of fundamental symmetries in low energy systems provide a complementary platform to high-energy colliders for exploring new physics beyond the Standard Model. A more precise value for the permanent electric dipole moment of the electron (eEDM, d_e) will have important implications for various extensions of the Standard Model. Trapped molecular ions offers key advantages such as long interrogating time, efficient quantum state control, and robust techniques to search for systematic effects. The Gen I JILA eEDM measurement using trapped HfF^+ constrains $|d_e| < 1.3 \times 10^{-28}$ e.cm (90% confidence) [**1**]. Here, we present the progress of ongoing Gen II and III experiments for better eEDM sensitivities. In Gen II, we increase the signal count rate by a factor of 100 by constructing a new ion trap with larger volume, increasing the polarizing E-field, and improving the efficiencies of state preparation and detection [**2**]. In Gen III, we use ThF^+ to replace HfF^+, because the eEDM-sensitive state ($^3\Delta_1$) of ThF^+ is the ground state [**3**], with a projected coherence time on the order of a few minutes, and the effective electric field (35.2 GV/cm) of ThF^+

[**4**] is 50% larger than that of HfF^+, which promises a direct increase of the eEDM sensitivity. To take full advantage of the long coherence time, we are designing a new ion trap that enables 100-fold multiplexed measurements. Our Gen II will be of comparable sensitivity to the current best measurement set by the ACME collaboration [**5**], while we expect two orders of magnitude improvement in our Gen III experiment.

[1] W. B. Cairncross *et al.*, Physical Review Letter. 119, **1** (2017)
[2] Y. Zhou *et al.*, In preparation
[3] D. N. Gresh *et al.*, Journal of Molecular Spectroscopy. 319, **1** (2016)
[4] L. V. Skripnikov *et al.*, Physical Review A. 91, **042504** (2015)
[5] V. Andreev *et al.*, Nature. 562, **355** (2018)

Thursday, July 25, 13:45–14:15

Honeywell's trapped ion quantum computer

Brian Neyenhuis[1]

[1]Honeywell Quantum Solutions

Honeywell Quantum Solutions (HQS) is pursuing a scalable quantum computing architecture based on trapped atomic ions. To this end, HQS is developing a broad array of enabling technologies and capabilities, including demonstrations of high-fidelity single- and two-qubit gates, fast ion transport and ion crystal reconfiguration, parallel multi-zone laser addressing of trapped ion qubits, and the design and microfabrication of state-of-the-art multi-zone ion traps. We will report recent progress on these and other fronts.

Thursday, July 25, 14:15–14:45

Scaling Trapped Ion Quantum Computing

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Chains of trapped ions provide an ideal platform for quantum computing, owing to their long coherence times and inherently identical nature, together with well-established techniques for high fidelity gate operations. At IonQ we are working to scale up trapped ion quantum computing, following the general architecture laid out in [**1**]. A chain of trapped $^{171}Yb^{+}$ ions is used as qubits, each individually addressed with a separate, controllable beam. In this way, we are able to drive arbitrary gates between any pair of ions, with full connectivity.

In this talk, I will present our latest results. These include recent benchmarking results with the Bernstein-Vazirani and Hidden Shift algorithms [**2**], and quantum chemistry simulations of the water molecule [**3**]. I will also discuss new techniques we have developed. These include new approaches to creating entangling gates, which allow running many gates in parallel within a single chain [**4**], and techniques for sideband cooling many motional modes in parallel.

[1] C. Monroe *et al.*, Phys. Rev. A 89, 022317 (2014)
[2] K. Wright *et al.*, arXiv:1903.08181 (2019)
[3] Y. Nam *et al.*, arXiv:1902.10171 (2019)
[4] N. Grzesiak *et al.*, arXiv:1905.09294 (2019)

Friday, July 26, 09:00–09:30

Qubit Control and Microfabricated Surface Ion Traps

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Trapped ions are nearing the forefront of quantum information technology having demonstrated high-fidelity operations, flexibility in control, and full connectivity. Microfabricated surface electrode ion traps offer a clear advantage in this field by enabling the classical control necessary to manipulate long chains of ions. Sandia's High Optical Access (HOA) trap has been previously used to demonstrate high-fidelity single and two-qubit gates [**1**] along with quantum control on long chains [**2**]. Taking advantage of our state-of-the-art fabrication capabilities, our next generation ion trap aims to improve on the functionality of the HOA trap.

While trap architecture is an integral part of trapped ion qubits, high-fidelity qubit operations also require efficient cooling to the motional ground state. In $^{171}\mathrm{Yb}^{+}$, this is typically accomplished using Raman lasers to perform cooling on the motional sideband of the qubit transition. We take advantage of the moderate lifetime in the quadrupole $^{2}\mathrm{S}_{1/2}$ to $^{2}\mathrm{D}_{3/2}$ transition by implementing a technique used for cooling optical qubits [**3**]. Using a narrow linewidth continuous wave laser, we resolve the motional sidebands of the quadrupole transition to perform sideband cooling.

Another long standing problem for high-fidelity qubits is stabilizing the environment. Small changes in electric or magnetic fields can have a large impact on the qubit transition frequency. To mitigate these effects, we demonstrate drift measurement and control. By implementing a time resolved analysis technique, we determine the dominate frequency components behind the drift. Then, we feedback on the critical parameters to account and compensate for this drift. The resulting analysis could not discern any remaining fluctuations or drift in the qubit.

[1] R. Blume-Kohout *et al.*, Nature Communications 8, 14485 (2017).
[2] K. Wright *et al.*, arXiv:1903.08181 (2019).
[3] F. Diedrich, J. C. Bergquist, W. M. Itano, and D. J. Wineland. Phys. Rev. Lett. **62**, 403 (1989).

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Friday, July 26, 09:30–10:00

Integrated Technologies for Enhanced Control of Trapped-Ion Systems

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Trapped-ion-based quantum information processing (QIP) has the potential for improved computation and sensing, but current methods for ion manipulation and state control present challenges to building larger-scale systems while maintaining high operation fidelity. Promising techniques and technologies must be developed and bench-marked in order to guide the design of architectures that can enable practical trapped-ion QIP without introducing significant error. We are investigating integrated electronics for ion-motion control and integrated optics for laser-based state preparation, measurement, and quantum logic in multi-species systems, as these technologies may lead to lower-error operations while also potentially providing a route to controlling many ion qubits. We will describe recent progress in this area, as well as in the demonstration of multi-qubit operations in Ca^+/Sr^+ crystals, particularly promising dual-species systems due to the integration-friendly control wavelengths.

Friday, July 26, 10:00–10:30

Adsorbate-coverage-dependent work-function patches on Au ion-trap electrodes

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Inhomogeneities on an electrode surface cause surface-potential patches, or spatial distributions of local work functions. These include regions of different composition, adsorbate coverage, crystallographic orientation and topographic morphology. If a dynamic mechanism causes the work function of these patches to fluctuate temporally, the result is electric-field noise above the electrode. In an ion trap, this noise couples to the ion's charge at its location and mode frequency and can cause motional heating. Motional heating from nearby surfaces is a problem for some high-precision measurements with trapped ions.

In this work, surface-potential patches were measured spatially on a Au "test" ion-trap electrode with Kelvin probe force microscopy (KPFM) as a function of adsorbate coverage and topographic morphology. The coverage was incrementally reduced from the native carbonaceous contamination thickness via Ar^+ bombardment. The thickness and composition of the surface were measured with x-ray photoelectron spectroscopy. Average patch-size radii on the order of 50 nm were observed in KPFM images with wide multi-peak work-function distributions.

In this talk, these results will be compared and contrasted with work-function measurements of a model system, namely, atomic carbon deposited on a Au(110) single crystal [**1**]. The KPFM results will also be presented alongside heating-rate data from an ion trap with *different* Au electrodes, but similarly treated with incremental Ar^+ bombardment. A simple model that supposes that the magnitude of electric-field noise is dependent on the adsorbate coverage θ *and* the slope of the work function ϕ, i. e., $d\phi/d\theta$, will be considered to qualitatively interpret the nonmonotonic heating-rate data previously reported in [**2**].

[1] H. Z. Jooya *et al.*, Surf. Sci. **677**, 232 (2018).
[2] E. Kim *et al.*, Phys. Rev. A **95**, 033407 (2017).

Friday, July 26, 11:15–11:45

Progress in Engineering Ion Trap Quantum Computers

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Pushing trapped ion systems from scientific experiments to practically viable quantum computing systems requires substantial advances in system integration technologies, starting from hardware components to assembly and test procedures, to control optimization through advanced software, to quantum computer system architectures and algorithm mapping. Innovation in solving practical problems arising from these challenges form the foundation of the engineering approaches in trapped ion quantum computing. In this talk, I will describe the prioritization of the technical challenges defined by the goal of practical quantum computation, and describe the technology solutions we have been developing in our laboratory at Duke. We will discuss advanced photon detectors used for efficient qubit state detection [**1**], new framework for developing stable optical assemblies, system design strategy for cryogenic system operation, efficient loading of ions using laser ablation, alternate approaches to ultra-high vacuum chamber solution, and design and characterization approaches for implementing high fidelity quantum logic gates.

[1] S. Crain *et al.*, arXiv:1902.04059 (2019).

Friday, July 26, 11:45–12:15

Quantum-classical hybrid circuits with trapped ions

N. M. Linke[1], D. Zhu[1], O. Shehab[2], N. H. Nguyen[1], C. H. Alderete[1,3], K. A. Landsman[1], T. Hsieh[4], S. Johri[5], M. Benedetti[6], R. C. Pooser[7], and C. Monroe[1,2]

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Quantum-classical hybrid systems offer a path towards the application of near-term quantum computers to different optimization tasks. They are attractive since part of the effort is outsourced to a classical machine resulting in shorter and narrower quantum circuits, which can be executed with lower error rates. Several applications are currently being discussed and investigated in this context, such as the Variational Quantum Eigensolver (VQE) for eigenvalue approximation problems, or the Quantum Approximate Optimization Algorithm (QAOA) for combinatorial optimization problems.

We present several demonstrations relating to the hybrid approach, such as finding the ground state binding energy of the deuteron nucleus with VQE [**1**], the training of shallow circuits for generative modeling using a Bayesian optimization strategy [**2**], tackling the Max-Cut problem using QAOA [**3**], and the preparation of quantum critical states with a QAOA-inspired scheme [**4**].
Our experimental system combines different classical optimizers with a programmable trapped-ion quantum computer comprised of a chain of $^{171}Yb^{+}$ ions. The latter features individual Raman beam addressing and individual readout, and can be configured to run any sequence of single- and two-qubit gates [**5**].

Recent results, limitations of the above methods, and ideas for boosting these concepts for scaling up the quantum-classical hybrid architecture will be discussed.

[1] O. Shehab *et al.*, arXiv:1904.04338 (2019)
[2] D. Zhu *et al.*, arXiv:1812.08862 (2018)
[3] O. Shehab *et al.*, arXiv:1906.00476 (2019)
[4] D. Zhu *et al.*, arXiv:1906.02699 (2019)
[5] S. Debnath *et al.*, Nature **563**:63 (2016)

Hot Topics

Time	Name	Poster No.	Title
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Poster abstracts

Poster No. 1

Progress on micro ion traps with scalable microwave control

A. Bautista-Salvador[1,2], H. Hahn[1,2], G. Zarantonello[1,2], J. Morgner[1,2], A. Preciado-Grijalva[1], M. Wahnschaffe[1,2], and C. Ospelkaus[1,2]

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We present advances on the application of a novel method for the realization of large-scale quantum devices [**1**]. We will detail on the trap fabrication and show preliminary results on the characterization of a multilayer ion trap with integrated 3D microwave circuitry towards the implementation of high-fidelity quantum logic control on $^{9}\mathrm{Be}^{+}$ ions [**2**]. We demonstrate ion trapping, simple microwave control on a laser cooled $^{9}\mathrm{Be}^{+}$ ion held at a distance of 35 μm. We extract the characteristics of the near-field using a 2D near-field model [**3**] and compared to numerical simulations. Finally, we present new routes and potential devices in which the multilayer method can be exploited.

[1] A. Bautista-Salvador *et al.*, New J. Phys. 043011, **21** (2019)
[2] H. Hahn, G. Zarantonello *et al.*, ArXiv:181202445, (2018)
[3] W. Wahnschaffe *et al.*, Appl. Phys. Lett. 034103, **101** (2017)

Poster No. 2

Quantum simulation and sensing with 2D arrays of hundreds of trapped ions

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We summarize recent experimental work with 2D arrays of hundreds of trapped $^9Be^+$ ions stored in a Penning trap. Electromagnetically induced transparency (EIT) cooling has recently been implemented[**1**], with near ground state cooling observed for all the drumhead modes. Future experiments will investigate extending EIT cooling to 3D crystal arrays. We also discuss improvements in the phase stability of the spin dependent, optical-dipole force, which enables new phase-coherent force sensing protocols, and the reduction of spontaneous emission in quantum simulation through parametric amplification. Preliminary force sensing experiments carried out with an rf tickle far from the axial center-of-mass (COM) mode show a single measurement enhancement of more than 10 over previous work[**2**].

[1] J.E. Jordan et al., PRL 122, 053603; A. Shankar et al., PRA 99, 023409 (2019).
[2] K.A. Gilmore et al., Phy. Rev. Lett. **161**, 263602 (2017).

Poster No. 3

Ultra-low heating rates for high precision measurements on antiprotons

M. J. Borchert[1,2], *et al.*, on behalf of the BASE colloboration

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The observed baryon asymmetry in our universe challenges the Standard Model of particle physics and motivates sensitive tests of the CPT invariance. Inspired by this, the BASE experiment at CERN compares the fundamental properties of antiprotons and protons with high precision using an ultra-low noise cryogenic multi-Penning trap apparatus.
One particular challenge is imposed by electric-field noise that fundamentally affects the spin-state detection fidelity in magnetic moment measurements. Recently, we reported on the first heating rate determination in a cryogenic Penning trap [**1**], the measured electric field noise is more than 100 times better than in room temperature Penning traps and more than 1000 times lower as in Paul traps. In this contribution, recent experimental developments and future measurement prospects will be discussed.

[1] M. J. Borchert *et al.*, Phys. Rev. Lett. 122, **043201** (2019)

Poster No. 4

Multi-Qubit Logic Primitives in Mixed-Species Ion Crystals

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Trapped-ion quantum processors equipped with more than one atomic species offer many potential advantages over traditional single-species systems. For example, ions of a second species can be used as ancilla ions whose control fields will not decohere the quantum states of the computational qubits. These ancillas can be used for a variety of tasks relevant to quantum processing, such as sympathetic motional cooling and low-crosstalk state readout. Here we demonstrate a suite of multi-qubit operations that serve as key quantum logic primitives in a number of different $^{40}\mathrm{Ca}^{+}/^{88}\mathrm{Sr}^{+}$ ion crystals. The optical qubits housed in $^{40}\mathrm{Ca}^{+}$ and $^{88}\mathrm{Sr}^{+}$ are particularly appealing, as the laser light used to drive qubit state transitions is at 729 nm and 674 nm, respectively. These red wavelengths are compatible with a host of integrated photonic technologies that can dramatically simplify beam routing for sophisticated ion trapping geometries.

Poster No. 5

Manipulation of Yb ions with segmented blade trap

M.-L. Cai[1], Q.-X. Mei[1], M.-M. Cao[1], R. Yao[1], X. Zhang[1,2], L.He[1], Z.-C. Zhou[1], and L.- M. Duan[1]

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We set up a segmented blade trap for quantum computation and quantum simulation experiments with Yb ions. After locking the 369.5nm diode laser to a pre-stabilized cavity, we implement efficient state preparation and detection by a moderate N.A. ($\sim$0.27) objective of the magnetic field-insensitive hyperfine levels of $^{171}Yb^{+}$. With trapped single ion, we achieve an average state detection fidelity around 98.5% and the pumping error below 1.5%. With 355nm Raman laser, we successfully implement the σ_ϕ force to a single ion which is a prerequisite for entanglement gates of ions.

We also construct a 435.5nm ultra-narrow linewidth laser for $S_{1/2}$ to $D_{3/2}$ transition to test some new schemes of manipulation of Yb ions. A cryogenic system is under construction to achieve larger-scale ion chains for quantum simulation and quantum computation.

Poster No. 6

Design of a Planar Penning Ion Traps for Scalable Quantum Information Experiments

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I will describe a new experimental setup we are building to explore quantum computation and simulation using ions trapped in individual sites of an array of micro-Penning traps. This avoids the need for radio-frequency fields which pose significant challenges for scaling micro-fabricated Paul traps, and opens new possibilities. For quantum computing in the QCCD architecture, one is that the magnetic field of the Penning trap is homogeneous, facilitating reconfiguration of 2-D arrays without using special junction trap regions. For quantum simulation, our approach allows strongly coupled static arrays with the possibility for engineering spin and motional interactions[**1**]. First experiments will aim at mastering control of single ions in a microfabricated traps, including studies of loading, cooling and heating.

[1] S. Jain et al., arXiv:1812.06755, (2018)

Poster No. 7

$^{138}Ba^+$ and $^{171}Yb^+$ Dual Species Modular Quantum Network

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To address the challenge of scaling trapped ion systems, we utilize a modular architecture consisting of separate traps with photonic links for remote entanglement. In our experiment, each trap contains a $^{171}Yb^+$ memory qubit and a $^{138}Ba^+$ communication qubit. We report progress in the development of this system, including improvements in light collection, higher purity of the single photons generated for remote entanglement, increased fidelity in our ion-photon entanglement, and the construction and integration of the second module. The outlook toward a three trap system is discussed.

Poster No. 8

Detection of trapped ion oscillations via optical interferometry

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We present an experiment that detects the oscillations of a trapped ion near its motional ground state. We laser cool and confine Ba^+ ions in a linear Paul trap and use the ion spontaneous emission in an interferometric setup. Interference is produced by reflecting part of the emitted light onto the ion, which modulates the detected photon rate depending on the ion position [**1**]. While laser cooling at the Doppler limit, we observe the frequencies of the ion's normal modes simultaneously, and reconstruct trajectories in phase space for a driven system. For one ion prepared in the ground state, we reach a sensitivity of a single quantum of motion. Furthermore, we observe the oscillations of a two-ion string. This technique can be improved to investigate quantum states of motion and measure the oscillations of mixed-ion systems.

[1] P. Bushev *et al.*, Phys. Rev. Lett. **96**, 043003 (2006)

Poster No. 9

Developing trapped-ion quantum computers at IonQ

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The field of quantum computation has grown dramatically in the past decades, and the potential capabilities and applications of quantum computers have attracted broad interests in both academia and industry. At IonQ, Inc., we are developing universal quantum computers based on trapped ions. To this end, we theoretically and experimentally investigate new technologies including quantum gate design, quantum circuit optimization, ion trap and system development, benchmarking techniques, and application demonstrations [**1**]. In this poster, we will present our recent efforts towards building a scalable quantum computer.

[1] N. Grzesiak *et al.*, arXiv:1905.09294 (2019);
R. Blumel *et al.*, arXiv:1905.09292 (2019);
K. Wright *et al.*, arXiv:1903.08181 (2019);
Y. Nam *et al.*, arXiv:1902.10171 (2019).

Poster No. 10

High fidelity operation of a synthetic spin-1/2 hyperfine qubit

Justin E. Christensen[1], David Hucul[1], Wesley C. Campbell[1], and Eric R. Hudson[1]

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The recent trapping and laser cooling of $^{133}Ba^+$ has opened the door to the use of this nearly ideal atom for trapped-ion quantum information processing. However, before ultrahigh-fidelity qubit operations can be performed, a number of unknown state energies are needed. Here, we report measurements of the $^2P_{3/2}$ and $^2D_{5/2}$ hyperfine structure, as well as the $^2P_{3/2} \leftrightarrow {}^2S_{1/2}$ and $^2P_{3/2} \leftrightarrow {}^2D_{5/2}$ transition frequencies. Using these transitions, we demonstrate ultrahigh fidelity $^{133}Ba^+$ hyperfine qubit manipulation with electron shelving detection to benchmark qubit state preparation and measurement (SPAM). Using single-shot, threshold discrimination, we measure an average SPAM fidelity of $F = 0.99966(5)$, a factor of 2 improvement over the best reported performance of any other qubit.

Poster No. 11

Logical Cooling for Robust Analogue Quantum Simulation

S. M. Clark[1], C. W. Hogle[1], J. S. Stephens[1,2], K. Young[1], R. Blume-Kohout[1], D. Stick[1], and P. Maunz[1]

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Analogue quantum simulation is arguably the most promising near-term application of quantum computing. However, analogue simulators are susceptible to noise, and it is not known if realistic noise destroys their computational power. Here, we report our progress using a technique to remove errors in the computational basis of the system, without resorting to a full error correcting scheme, to both measure and increase an analogue quantum simulator"s robustness to noise.

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Poster No. 12

Preparation and Coherent Manipulation of a Single Molecule

A. L. Collopy[1], C-W. Chou[1], Y. Lin[2], C. Kurz[1], T. Fortier[1], S. Diddams[1,3], D. Leibfried[1], and D. R. Leibrandt[1,3]

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Using quantum logic techniques, we perform precision spectroscopy as well as coherent quantum state manipulation of a molecular ion [**1**]. The protocol and apparatus used should be broadly extensible to a wide variety of molecular species, including polyatomic ions. Using a CaH^+ molecule co-trapped with a logic Ca^+ atomic ion, the coupled motional state of the molecule-atom ion pair is used as an information bus, and the completion of a molecular transition is heralded by a detectable state change of the Ca^+ ion. When such a transition has a unique frequency, the molecule is projectively determined to be in a pure molecular quantum state. After this initialization, we perform spectroscopy with sub-kHz frequency resolution on THz scale rotational transitions, and anticipate improvement to the sub-Hz level.

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

Poster No. 13

Diffraction Grating Spectrometer for Frequency Qubit Detection

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Trapped ion quantum networking requires photons to connect distant ion trap platforms, ideally in the telecom range. However, most ions do not emit in this range and thus frequency conversion can be used to overcome this. Our system is a surface trap for $^{171}\mathrm{Yb}^{+}$ with integrated diffractive mirrors which we use to create ion-photon entanglement [**1**]. We have built a UV diffraction grating spectrometer to benchmark ion-frequency qubit correlations, it separates and images the frequency qubits achieving a spot separation of 2.7 ± 0.1 spots ($1/e^2$ dia.) which gives a theoretical fidelity of separation of >99%. This will allow us to characterise the fidelity of the UV to telecom conversion process for which we plan to use periodically poled lithium niobate.

[1] M. Ghadimi *et al.*, NPJ Quantum Information. vol. 3, no. 1, pp. 1-4. (2017)

Poster No. 14

Scalable Quantum Gate Implementation and Characterization in a $^{171}Yb^{+}$ Based Quantum Information Processor

S. Crain[1], Y. Wang[1], C. Fang[1], B. Zhang[1], and J. Kim[1]

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This work characterizes the performance of a $^{171}Yb^{+}$ based quantum information processor with up to five qubits with a surface trap. Single qubit gates are driven by Raman transitions using a pair of tightly focused co-propagating beams, and these beams are steered across the qubits using microelectromechanical system (MEMS) tilting mirrors. Composite pulse sequences (BB1 and SK1) are implemented in order to suppress amplitude noise during single qubit gates. Photons scattered by each of the qubits in a linear chain are coupled into individual fibers in a fiber array and sent to separate detectors for individual qubit state detection [**1**]. This work also characterizes Mølmer-Sørensen gates on pairs of ions. In a two qubit register, the single and two qubit gate fidelies are measured to be >99.98% and >99%, respectively. Characterization is ongoing for a five qubit register.

[1] S. Crain *et al.*, arXiv:1902.04059

Poster No. 15

Time resolved state detection with broadband pulses

Thomas Dellaert[1], Conrad Roman[1], Anthony Ransford[1], and Wesley C. Campbell[1]

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Projective readout of quantum information stored in atomic hyperfine structure typically uses state-dependent CW laser-induced fluorescence. This method requires an often sophisticated imaging system to spatially filter out the background CW laser light. We present an alternative approach that instead uses simple pulse sequences from a mode-locked laser to effect the same state-dependent excitations in less than 1 ns. The resulting atomic fluorescence occurs in the dark, allowing the placement of non-imaging detectors right next to the atom to improve the qubit state detection efficiency and speed. We discuss the shaping of the broadband pulse using a Mach-Zehnder interferometer in order to regain hyperfine state selectivity for the excitation. A single-pulse version of this scheme is easy to implement for optical frequency qubits and can be used to reject background scatter after shelving.

Poster No. 16

Progress on a Quantum-Logic Al^+ Ion optical clock in HUST

K. Deng[1], H. Liu[1], W. Yuan[1], Z. Ma[1], P. Hao[1], W. Wei[1], and Z. Lu[1]

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A $^{25}Mg^+$-$^{27}Al^+$ quantum logic optical clock [**1**] is under construction at Huazhong University of Science and Technology. Here we report progress on the clock. First, we report the sympathetic Raman sideband cooling of the $^{25}Mg^+$-$^{27}Al^+$ ion pair. We cooled both the common mode and stretch mode of the ion pair on axial direction to the motional ground state. Second, we report the observation of the $|^1S_0\rangle$ to $|^3P_1\rangle$ transition of the Al $^+$ ion based on the quantum logic spectroscopy. At last, we report the observation of the $|^1S_0\rangle$ to $|^3P_0\rangle$ clock transition of the Al $^+$ ion. Currently the linewidth of clock transition is nearly 800 Hz. We experimentally investigate the decoherence of clock transition spectrum and the optimization on the linewidth-narrowing of the spectrum. [**1**].

[1] D. J. Wineland *et al.*, J. Res. Natl. Inst. Stand. Technol. 103, **259** (1998)

Poster No. 17

Towards Nondestructive State Readout of a Single Molecule

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There is growing interest in precision spectroscopy of molecules, since the added internal degrees of freedom can be used in probes of fundamental physics. Vibrational overtones have a dependence on the proton-to-electron mass ratio, making these potentially optical transitions excellent candidates for a time variation measurement. We aim to do this through spectroscopy of the v = 0 to v = 3 overtone transition in AlH^+ co-trapped with a single Ba^+. While the mass ratio of the two ions, $\sim$5, makes sympathetic cooling challenging, it is beneficial to our unique state readout method. Repeated photon recoils due to absorption, achievable only if the molecule is in the ground electronic and vibrational state, will excite a phonon in the ion crystal, a process we call Photon Recoil Readout (PRR). We present our progress towards implementing PRR and discuss goals of precision spectroscopy on molecular states.

Poster No. 18

Progress Towards a High-Accuracy Transportable Single Ion Optical Clock at NRC

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The $^{88}Sr^{+}$ ion system is well-suited to realize high-accuracy transportable optical clocks. The accuracy of the $^{88}Sr^{+}$ ion is obtained using robust and reliable methods that yield very high cancellation of important systematic shifts such as the electric quadrupole shift [**1**] and the micromotion shifts [**2**]. These methods are easily implemented in a transportable system. A significant reduction in the size of the laser systems is obtained by using amplified spontaneous emission (ASE) sources for the repump and clearout lasers [**3**]. The operation of the $^{88}Sr^{+}$ clock and preliminary results with the ASE sources will be presented at the conference.

[1] P. Dubé *et al.*, Phys. Rev. Lett. **95**, 033001 (2005).
[2] P. Dubé *et al.*, Phys. Rev. Lett. **112**, 173002 (2014).
[3] T. Fordell *et al.*, Opt. Lett. **40**, 1822–1825 (2015).

Poster No. 19

Inter-site Coupling and Interference in a scalable 2D Trap Array

F. Hakelberg[1], P. Kiefer[1], M. Wittemer[1], U. Warring[1], and T. Schaetz[1]

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Atomic ions trapped in multi-dimensional arrays of individual potentials provide a promising approach towards scalable quantum simulations of more-than-one dimensional systems coupled at long-range. The coupling between two minima along a linear trap has been demonstrated [**1**], while inter-site coupling in two-dimensional approaches remained elusive. We previously realized a basic triangular array, based on scalable CMOS technology [**2**]. Here we present recent results, the realization of coherent inter-site coupling using large coherent states. We show real-time tuning of the coupling and the interference of coherent states in our two-dimensional array [**1**].

[1] M. R. Brown *et al.* & Harlander *et al.*, Nature **471**, 196-203 (2011)
[2] M. Mielenz *et al.*, Nature Communications **7**, 11839 (2016)
[3] F. Hakelberg *et al.*, arXiv:**1812.08552** (2019)

Poster No. 20

Characterization of a Structural Phase Transition at Ultracold Temperature

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We discuss our investigations of the linear-zigzag structural transition for arrays of ions confined in a linear radio-frequency Paul trap and laser-cooled to vibrational energies of a few quanta or less. Using Raman sideband spectroscopy, and enabled by a stabilized trap potential and low thermal fluctuations, we reveal effects close to the transition's critical point for small arrays of ions, including modifications to the nature of the transition. This work sets the stage for explorations of quantum coherence close to the critical point.

Poster No. 21

Hong-Ou-Mandel Interference between a trapped ion and Rydberg ensemble connected via a fiber link

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Future efforts to build distributed quantum networks will likely rely on the ability to interface or entangle disparate quantum systems. We demonstrate Hong-Ou-Mandel interference between photons generated on-demand by a barium ion and a rubidium Rydberg ensemble, located in separate buildings and linked over a fiber network. We use quantum frequency conversion [**1**] to spectrally match the center frequency of photons emitted by the ion to those produced by the neutral atom ensemble. With this result, we discuss potential rates and fidelities for ion-Rydberg ensemble entanglement. Our work forms the building blocks of a photonically linked hybrid ion-Rydberg ensemble quantum network.

[1] J. D. Siverns *et al.*, Phys. Rev. Applied **11**, 014044 (2019)

Poster No. 22

Highly-polarizable ion in a Paul trap

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Usually the influence of the quadratic Stark effect on an ion's trapping potential is minuscule and it only needs to be considered in atomic clock experiments. In this work we excite a trapped ion to a Rydberg state with polarizability $\sim$ eight orders of magnitude higher than a low-lying electronic state; we find that the highly-polarizable ion experiences a vastly different trapping potential owing to the Stark effect. We observe changes in trap stiffness, equilibrium position and minimum potential [**1**]. These effects lie at the heart of proposals to shape motional mode spectra [**2**], coherently drive structural phase transitions [**3**] and to carry out a fast entangling gate [**4**].

[1] G. Higgins *et al.*, arXiv:1904.08099 (2019)
[2] W. Li, and I. Lesanovsky, Phys. Rev. A **87** 052304 (2013)
[3] W. Li, and I. Lesanovsky, Phys. Rev. Lett. **108** 023003 (2012)
[4] J. Vogel *et al.*, arXiv:1905.05111 (2019)

Poster No. 23

A modular approach to a shuttling-based quantum processor in a 2D trap array

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We present progress on the implementation of a high fidelity logical qubit in an ion trap architecture designed for true scalability, based on global microwave-driven gates and physical shuttling of ion qubits.

We show an X-junction surface ion trap with dedicated zones optimised for ion loading, memory, entangling interactions, and readout [**1**]. Individual physical qubits are defined by dressed hyperfine states of the $^{171}Yb^{+}$ ion, addressed by their position in a magnetic field gradient, and noise-resilient spin-motion entanglement is driven by multi-tone microwave fields[**2**].

[1] Lekitsch, B. et al. Science Advances 3, **e1601540** (2017)
[2] Weidt, S. et al. Phys. Rev. Lett. 117, **220501** (2016)

Poster No. 24

Trap Microfabrication Capabilities and Demonstration of Sideband Cooling through the ^{171}Yb^{+} Quadrupole Transition

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Microfabrication enables the repeatable production of complex surface electrode ion traps. These traps allow for ion transport and for multiple and longer chains of ions. Here, we discuss our state-of-the-art trap fabrication capabilities for ion traps using up to 6-level metallization, and we present our latest trap designs. To demonstrate trap stability, we characterize and minimize the drift in single qubit microwave gate sequences. Furthermore, we introduce a sideband cooling technique involving the $S_{1/2}$ to $D_{3/2}$ transition on a ^{171}Yb^{+} ion as a simple method of characterizing ion heating rates.

[1] SNL is managed and operated by NTESS, LLC, a subsidiary of Honeywell International, Inc., for the US DOE NNSA under contract DE-NA0003525. This research was funded by IARPA. The views expressed here do not necessarily represent the views of the DOE, IARPA, or the U.S. Government.

Poster No. 25

Towards scalable quantum computing in a cryogenic surface trap

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Trapped atomic ion systems have demonstrated the prerequisite quantum control to implement universal gate sets for performing arbitrary quantum algorithms. The main challenge remains in scaling up the number of qubits such that quantum error correction on a logical qubit can be implemented. To push towards a scalable design, we work with strings of ions in a cryogenically cooled planar surface trap with multiple trapping zones [**1**]. Our setup supports the trapping of two ion species, $^{40}Ca^{+}$ and $^{88}Sr^{+}$, where the Sr ion can either be used for sympathetic re-cooling of the motional modes of the ion string or additional coherent control. The Ca^{+} ion acts as an optical qubit with coherence times of up to 11.5 ms. The low heating rate of the axial motion at 1.1 MHz of 12.7(13) phonons/s allows us to perform maximally entangling Ca^{+}- Ca^{+} gates with fidelities of 98(3)% and 90(3)% for 2 and 4 ions respectively. A 0.8 NA lens yields two ion state discrimination error of 10^{-3} in 100 μs.

[1] M. Brandl *et al.*, Rev. Sci. Inst. 87, **11** (2016)

Poster No. 26

^{133}Ba$^+$: high fidelity goldilocks qubits

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Hyperfine qubits with nuclear spin I = 1/2 have demonstrated the longest qubit coherence times with simple, robust laser manipulation. Other hyperfine qubits (I $\neq$ 1/2) have long-lived metastable electronic excited states, and simple discrimination between these states and the ground states results in the highest fidelity readout of an 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 naturally-occurring spin I = 1/2 nuclei are in the ultra violet. We demonstrate qubit manipulation of an artificial, I = 1/2 species of barium: ^{133}Ba$^+$. This ion has easily-prepared and long-lived metastable excited states and visible wavelengths for laser cooling. We achieve single shot qubit state preparation and readout fidelity F = 0.9997.

Poster No. 27

High-fidelity mixed-species entangling gates

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Trapped ions are a promising candidate for building a quantum computer - the qubits have long coherence times, and state-preparation, readout, single- and two-qubit operations have all been demonstrated with fidelities above the threshold for quantum error correction. However, increasing the number of qubits without increasing errors is challenging. One approach is to network many small ion-trap nodes via photonic links. Combining two different atomic species in each node allows sympathetic cooling of the ion crystal as well as emission of entangled photons from one species without corruption of the electronic state of the other. Entangling gates between the two species are essential in this scheme. We present two-qubit gates between $^{43}Ca^{+}$ and $^{88}Sr^{+}$ with fidelity 99.5(3)%, pushing mixed-species gate fidelities closer towards the best single-species gates. We show how to use this operation to enhance the coherence time of the $^{88}Sr^{+}$ qubit. Finally we demonstrate a first characterisation of our gate using two-qubit randomized benchmarking.

Poster No. 28

Demonstration of $^{171}Yb^{+}$ Qubit Operations in a Cryogenic Compact Packaged Surface Trap

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Cryogenic environments can be beneficial for ion trap setups by offering lower motional heating rates and an extreme-high vacuum environment for maintaining large ion chains for extended periods of time. Here, we present a novel ion trapping system where a low-vibration (<20 nm pk-pk) closed-cycle cryostat is utilized in a custom monolithic optical enclosure for high stability operation. Additionally, we use a compact package approach for installing surface traps into the cryostat, enabling easy handling, quick integration and characterization. Here, we show details about these compact packages and present results of background gas collision rate measurements with ions as a probe of vacuum conditions. We use $^{171}Yb^{+}$ qubits to measure heating rates and show results of qubit operations implemented with 355nm optical fields.

Poster No. 29

Laser cooled radium: progress and prospects

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Radium, the heaviest alkaline earth element, is promising for studying fundamental symmetries due to its high mass and octupole deformed nucleus. The high mass is also appealing for metrology and, somewhat surprisingly, quantum information science. We present on recent laser cooling of radium ions. We will discuss our measurements of the system's basic structure, enabled by laser cooling and state detection. Additionally we will present on production and future directions with the polyatomic molecular ion, $RaOH^+$. Radium's lack of stable isotopes is not a barrier because ion traps are well-suited to working with small samples that have very low activity. We discuss our plans to work with radium-225 and radium-224, isotopes with 15 and 3.7 day half-lives, in a table-top experiment.

Poster No. 30

A silicon-based microfabricated surface-electrode ion trap for modular quantum computing

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We have built a microfabricated surface trap for quantum computation and simulation experiments. The trap potential, ion chain dynamics as well as electrical properties are optimized during design. The surface trap was fabricated through standard MEMS processes from a silicon substrate and then standardized on a 100-pin CPGA architecture. Low-cost homemade devices including a wireless DAC module, a high-speed PMT counter and a high-resolution motorized stage are also adopted.

We have successfully trapped Yb^+ ions on this surface trap. After optimization of trapping parameters, we have measured the dark lifetime and heating rate through Doppler recooling method. A beatnote locking for Raman laser has been set up and will be incorporated in this system for future experiment.

Poster No. 31

A novel compact transportable multi ion clock setup

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Already excellent clocks based on single trapped ions can be further improved by using multiple ions allowing to benefit from shorter averaging times or advanced read-out schemes. Within the opticlock project [**1**], we are working on a demonstrator of a transportable commercial single ion clock and its upgrade to multi-ion operation with low frequency uncertainties. For this multi-ion frequency standard, a novel segmented four layer ion trap is combined with excellent optical access, a dedicated compact vacuum interface, and customized vacuum setup.

[1] opticlock is supported by the bmbf under grant no. 13N14385.

Poster No. 32

Sinara: open source modular hardware for quantum physics

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[3]Oxford University
[4]NIST [5]M-Labs
[6]QUARTIQ [7]Creotech Instruments

The Sinara hardware platform is a 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 standard and Eurocard Extension Modules (EEM). The hardware modules can be combined in several configurations, starting from low-cost single box device attached to the PC up to full experiment control systems covering all needs of complex laboratory setup. The hardware is controlled and managed by the ARTIQ, an open-source software developed by M-Labs. ARTIQ provides high-level programming language that enables describing complex experiments with nanosecond timing resolution and submicrosecond latency. The system currently consists of nearly 40 different modules with more under active development[**1**].

[1] https://sinara-hw.github.io/

Poster No. 33

Segmented RF Trap for 2D Ion Crystals

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Quantum computation in trapped ions is most commonly performed in linear Paul traps to avoid micromotion which is thought to lead to low gate fidelities. Recent theoretical work [**1**] shows that micromotion can be compensated for with the use of pulse shaping, allowing for fidelities >99.99% in two-dimensional ion crystals of >100 ions. Here, we seek to experimentally demonstrate high-fidelity quantum gates in Ba+ ions in a planar crystal. To do so, we have developed a novel trap system specifically for producing two-dimensional ion crystals. The trap is derived from the original Paul trap, with the ring electrode separated in eight identical segments that allow us dynamically tune the transverse trap aspect ratio to produce different planar crystals. In addition to high-fidelity gates, the system in development may also be used for quantum chemistry simulations and the study of crystalline order, defects, and phase transitions.

[1] S. T. Wang *et al.*, Scientific Reports. 5, 8555 (2015).

Poster No. 34

Floquet engineering of vibrational dynamics in a two-dimensional ion-trap array

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We present Floquet engineering of the vibrational dynamics in a basic but scalable two-dimensional triangular ion-trap array. In contrast to matching trapping frequencies [**1**], local parametric modulation of detuned trapping potentials permits the coupling between distant ions currently via large coherent states of motion. We tune the coupling by adjusting amplitude and phase of the modulation, controlling directionality and interferences of the phonon flow and its related Peierls phase. Assisted coupling has been proposed to substantially extend the toolbox for experimental quantum simulations, exploiting phonons and their pathways beyond mediating effective interactions [**2**].

[1] F. Hakelberg *et al.*, arXiv: 1812.08552 (2019)
[2] A. Bermudez *et al.*, PRL **107**, 150501 (2011)

Poster No. 35

Progress on the experimental setup for Software-Tailored Architecture for Quantum co-design (STAQ) project

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The aim of the STAQ project is to enable significant advances in quantum computational capability at the system level by full vertical integration from the qubit hardware to user-friendly software stack. To achieve this goal, we have been building the 1st generation STAQ quantum computer hardware based on trapped ions. This system adopts a custom cryostation with high mechanical stability and a compact ultra-high vacuum-sealed package that houses a Sandia high-optical access microfabricated trap to keep a long chain of $^{171}Yb^{+}$ ions to be used as qubits. The logic gates on these qubits are driven by optical Raman transitions controlled by a mutli-channel acousto-optic modulator. Two-qubit gates between arbitrary pair of qubits can be implemented in this system. We will present the details of the design and programming interfaces that will be used for software integration.

Poster No. 36

Quantum networking tools with single atoms and single photons

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In the context of quantum communication technologies, we are developing a comprehensive set of experimental tools, based on single photons and single atoms (trapped ions), that enable controlled generation, storage, transmission, and conversion of photonic qubits in quantum networks in a programmable manner [**1**]. As experimental applications, we demonstrate high-fidelity transfer of entanglement from a narrowband SPDC photon pair to atom-photon pairs, as well as atom-to-photon qubit teleportation [**2**]. We also extend our quantum network toolbox into the telecom regime by polarization-preserving quantum frequency conversion of atom-entangled photons [**3**].

[1] C. Kurz et al., Nat. Commun. **5**, 5527 (2014)
C. Kurz et al., Phys. Rev. A **93**, 062348 (2016)
[2] S. Kucera et al., in preparation
[3] M. Bock et al., Nat. Commun. **9**, 1998 (2018)

Poster No. 37

Study on the decoherence of phonon hopping in an ion chain

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We study quantum information processing and quantum simulation using the radial vibrational modes of $^{40}Ca^{+}$ ions in a linear trap. Hopping of local phonons is a phenomenon in which phonons jump to other ions due to Coulomb interactions, and it is actually observed in previous works [1-3]. Investigation of the decay factors in phonon hopping is important for applications using local phonons. We observed hopping dynamics and estimated decay times in various trap conditions. Based on the results, we discuss the relationship between trap condition and decay times in order to identify the decay factors.

[1] K. R. Brown *et al.*, Nature **471**, 196 (2011); M. Harlander *et al.*, Nature **471**, 200 (2011); S. Haze *et al.*, Phys. Rev. A **85**, 031401 (2012).
[2] K. Toyoda *et al.*, Nature **527**, 74 (2015).
[3] S. Debnath *et al.*, Phys. Rev. Lett. **120**, 073001 (2018).

Poster No. 38

Adsorbate-coverage-dependent work-function patches on Au ion-trap electrodes

F. Lancellotti[1], M. Marinelli[1], B. De Neeve[1], T. Behrle[1], M. Stadler[1], V. Negnevitsky[1], K. Mehta[1] and J. P. Home[1]

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I will describe our recent progress towards scaled up algorithms on calcium and beryllium ions in a segmented ion trap. In work on Moelmer-Sorensen gates, an automatic Bayesian calibration method based on a Gaussian particle filter has been used to calibrate a gate with fidelity of 98.1(4)% using only 1000 shots of the experiment, providing a significant improvement over manual methods. Integrated on-board analog feedback acquisition integrated into our DDS-based radio-frequency pulse synthesis have been used to defeat injected slow noise affecting single and multi-qubit quantum gates fidelities. In optimizing the system for shuttling mixed-species chains, multi-ion Ca^+ and Be^+ single species crystals have been separated with average excitations of 1.69(5) and 0.37(1) respectively.

Poster No. 39

Quantum jump dynamics in a trapped barium ion

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We are investigating the dynamics of quantum jumps in singly trapped barium ions. Our research follows the work of Minev et al[**1**], where they demonstrated the ability to catch and reverse quantum jumps mid-flight in an artificial superconducting "atom."

Our system is a modified Paul trap containing a parabolic mirror, which allows for light collection from 39% of the solid angle surrounding the trapped barium ion and a total detection efficiency (including collection and PMT quantum efficiency) of 8%. We expect to detect a photon about every 200ns, which would give us fine enough resolution to catch quantum jumps occurring on the time scale of microseconds.

[1] Z. K. Minev *et al.*, Nature. 1 (2019)

Poster No. 40

Global entangling gates on arbitrary ion qubits

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The decomposition of universal quantum computation by single and 2-qubit gates is not necessarily efficient, and can be speeded up with global N-qubit ($N > 2$) entangling gates[**1**]. The previous method to realize the global gates utilizes the well-isolated axial center-of-mass mode, which is difficult to scale up[**2**]. Here we propose and implement a scalable scheme on multiple $^{171}Yb^+$ ion qubits by coupling to multiple motional modes through modulated laser fields. To realize the global gates, we need to decouple multiple modes and balance all pairwise coupling strengths simultaneously. Thus, we develop a system with fully-independent control capability on each ion. To demonstrate usefulness and flexibility of the global gates, we generate a GHZ state up to four qubits with a single global operation. Our approach materializes the global gates as a scalable building block for universal quantum computation.

[1] D. Maslov *et al.*, New J. Phys. **20** 033018 (2018)
[2] T. Monz *et al.*, Phys. Rev. Lett. **106** 130506 (2011)

Poster No. 41

High Finesse Cavities for Ion Traps

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We will present the process that allowed us to manufacture and interface a short ($\approx$350 μm) and high (>50 000) finesse cavity with a segmented ion trap. Specifically, we will show fabrication methods based on subtractive 3D printing of fused silica (ion trap) and on CO2 laser ablation (high-finesse cavities). Those fiber or substrate cavities can be interfaced directly with the ion trap. We will introduce our solutions to overcome the technical challenges that come with the fabrication of a monolithic trap-cavity module that does not rely on complicated alignment procedures in vacuum. With this setup, we plan to reach the regime of strong ion-photon coupling i.e. to obtain deterministic interaction. Furthermore, this will serve as the basic building block of an optically connected Quantum Network.

[1] R.J. Hughes, PRL, **77**, 3240-3243 (1996)
[2] C. Monroe, PRA, **89**, 022317 (2014)

Poster No. 42

Anomalous scaling of anomalous heating in surface ion traps

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I will show recent results on the scaling of electric-field noise in surface traps from the Berkeley lab. In the first experiment we measure the temperature and frequency dependence in an aluminium-copper electrode trap between room temperature and 600 K. We observe a saturation of the noise amplitude around 500 K [**?**], and a distinct change in the noise at 600 K. The noise spectrum is consistent with noise generated by a distribution of thermally-activated two-level fluctuators.

In the second experiment we probe electric-field noise as a function of surface-ion distance in a novel trap geometry [**1**] and find a scaling of $S_E \sim d^{-2.6}$ for 50 μm $< d <$ 300 μm. Measurements of the noise amplitude both parallel and perpendicular to the trap surface rule out technical noise sources.

[1] D. An *et al.*, Review of Scientific Instruments **89** (9), 093102 (2018)

Poster No. 43

A versatile platform for segmented blade trap

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Several setups of segmented blade trap system have been deployed in lab, focusing on different applications including universal quantum computation and quantum simulation. Many techniques are utilized to make them more reliable and robust, including the frequency stabilization of 369nm diode laser with nonlinear spectroscopy of Ytterbium ions in a discharge lamp, a control system for automatic ion loading and real-time feedback based on ions status, an BEM-based simulaiton program for trap potential, and a reliable procedure to design helical resonator accurately with quality factor over 300. As our system is able to trap tens of ions, multiple ion detection with EMCCD has also been implemented, requiring about 1ms exposition time, and we are testing multiple ion detection with multi-channel PMT.

Poster No. 44

Light-matter entanglement over 50 km of optical fibre

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When shared between remote locations, entanglement opens up fundamentally new capabilities for science and technology. Envisioned quantum networks use light to distribute entanglement between their remote matter-based quantum nodes. Here we report on the observation of entanglement between matter (a trapped ion) and light (a photon) over 50 km of optical fibre. Our methods include an efficient source of ion-photon entanglement via cavity-QED techniques (0.5 probability on-demand fibre-coupled photon from the ion) and a single photon entanglement-preserving quantum frequency converter to the 1550 nm telecom C band (0.25 device efficiency). Modestly optimising and duplicating our system would already allow for 100 km-spaced ion-ion heralded entanglement at rates of over 1 Hz.[**1**].

[1] V. Krutyanskiy *et al.*, Light-matter entanglement over 50 km of optical fibre, arXiv:1901.06317 (2019)

Poster No. 45

Coherent Control of the Rotational Degree of Freedom of a Two-Ion Coulomb Crystal

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Historically, the control over shared motional modes of a trapped ion crystal is limited to modes of a linear chain that can be well described as harmonic oscillators. Here, we demonstrate coherent control of a collective motional state instead described as a quantum rotor, the dynamics of which are fundamentally different. The ions are prepared to be freely rotating at 100 kHz in a circularly symmetric potential, allowing us to address rotational sidebands. By coherently exciting these motional sidebands, we create superpositions of states separated by up to four angular momentum quanta. Ramsey experiments show the expected dephasing of the superposition which is dependent on the number of quanta separating the states. A full understanding of the decoherence mechanisms affecting these motional modes is ongoing.[**1**]

[1] E. Urban et al., ArXiV 1903.05763.

Poster No. 46

Towards testing CPT with the Molecular Antihydrogen Ion

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High precision radio-frequency, microwave and infrared spectroscopic measurements of the molecular antihydrogen ion $\bar{H}_2^-$ ($\bar{p}\bar{p}e^+$) compared with its normal matter counterpart H_2^+ provide direct tests of the CPT theorem [**1**]. The sensitivity to a difference between the positron/antiproton and electron/proton mass ratios, and to a difference between the positron-antiproton and electron-proton hyperfine interactions, can exceed that obtained by comparing antihydrogen with hydrogen by several orders of magnitude. Methods are outlined for measurements on a single $\bar{H}_2^-$ ion in a cryogenic Penning trap, that use non-destructive state identification by measuring the cyclotron frequency and bound-positron spin-flip frequency using the continuous Stern-Gerlach effect; and also for creating an $\bar{H}_2^-$ ion and initializing its quantum state. Steps towards implementing these ideas with H_2^+ will also be discussed. (Support from the NSF and the APS-Moore travel program.)

[1] E. G. Myers, Phys. Rev. A **98**, 010101(R) (2018).

Poster No. 47

A Miniature Electron Beam Ion Trap (mini-EBIT) for studying Highly Charged Ions with Low Ionization Threshold

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Recent studies indicate that certain highly charged ions (HCIs), 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**]. The proposed candidate ions(ionization thresholds up to 1000 eV) are more suitably produced in an electron beam ion source/trap (EBIS/T) with a lower magnetic field, compared with traditional EBITs with a strong field ($\sim$ 3 to 6 T). We have developed a room-temperature mini-EBIT with a dual-anode electron gun designed to alleviate the space charge effects for the low electron beam energy regime. We present detailed test results and capabilities of the mini-EBIT. Time-of-flight spectra of extracted noble gas HCIs are analyzed for the identification of ion species. Preliminary designs for a permanent magnet Penning trap and laser ablation-based metal injection are discussed.

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

Poster No. 48

Boosting variational quantum algorithms using past causal cones

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Hybrid quantum-classical algorithms such as VQE and QAOA have been proposed for finding approximate solutions to many classes of complex problems. So far, they lack the robustness to noise necessary to be applicable to NISQ devices. Here we develop a method to construct resource-efficient reduced circuit using past causal cones of terms in the target Hamiltonian. We demonstrate that this method enhances the read-out and process fidelity. Applying this method to different computing problems on a programmable trapped ion quantum computer[**1**], we find that compared to the original circuit the accuracy improves by $\sim 80\%$ for finding the Deuteron binding energy and by $\sim 60\%$ for the Max-Cut problem on the dragon graph $T_{3,2}$.

[1] S. Debnath *et al.*, Nature, **536**, 63-66 (2016)

Poster No. 49

Quantum Reservoir Engineering with Trapped Ions

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Active control of the coupling of a quantum system to its environment, a.k.a quantum reservoir engineering (QRE) has been proved to be a rich resource for quantum state preparation and quantum computation. It also provides the possibility to study open quantum systems, in particular quantum phase transitions driven by dissipation. The implementation of QRE with mixed species ion crystal will offer us a rich toolbox to explore this direction. As an example, I will present our recent numerical results involving the disspative version of the well-known Dicke model, where differ from a closed system, an open finite system exhibits a non-steady phase beside the (dissipative) superradiant phase.

I will also discuss our experimental avancement toward stable ion trap in cryogenic environment with realiable laser delivery based on on-chip integrated photonic waveguide.

Poster No. 50

High-rate, high-fidelity entanglement of qubits across a quantum network

L. J. Stephenson[1], D. P. Nadlinger[1], B. C. Nichol[1], S. An[1], P. Drmota[1], K. Thirmulai[1], J. F. Goodwin[1], D. M. Lucas[1], and C. J. Ballance[1]

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We demonstrate remote entanglement of trapped-ion qubits across a quantum-optical fiber link. Two $^{88}\mathrm{Sr}^+$ ions are entangled via the polarization degree of freedom of spontaneously emitted 422 nm photons. We find that coupling into single-mode fibre allows error-free photon collection orthogonal to the quantization axis even for large solid angles. Remote Bell pairs are generated with fidelity $F = 0.940(5)$ at an average rate of 182 Hz (success probability 2.2×10^{-4}).

Compared to previous work [**1**], this is a fourfold reduction in errors while increasing the entanglement rate by almost two orders of magnitude, with the rate now approaching that of local operations.

[1] D. Hucul et al., Nat. Phys. 11(1), 37 (2015).

Poster No. 51

Integrated multi-wavelength addressing of trapped ion qubits

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Integrating classical control technologies with quantum systems like trapped ions is a very promising route for the development of practical, high-fidelity quantum computers. For instance, individual addressing of trapped ion qubits typically requires bulky free space optics to tightly focus multiple laser beams onto single ions within linear chains, leading to control-field imperfections and limiting scalability. Here we have designed and fabricated an ion trap chip with integrated photonic waveguides and grating out-couplers for integrated addressing in all of the infrared, visible, and ultraviolet wavelengths required to cool and control $^{88}Sr^{+}$ trapped ion qubits. We study the interaction of these new multi-wavelength photonics with a single ion qubit towards demonstration of a two qubit gate controlled via integrated technologies, a key component of a scalable trapped ion quantum information processor.

Poster No. 52

Toward Continuous-Time Cyclic Quantum Walks using a Trapped-Ion Quantum Rotor

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We propose two experimental realization schemes of the continuous-time cyclic quantum walks using a trapped-ion quantum tunnelling rotor [1]. The main idea of the cyclic quantum walks using a trapped-ion quantum tunnelling rotor [2] is to measure the time evolution of the population of the ion having the different internal state. This study offers experimental realization schemes for the continuous-time cyclic quantum walks.

[1] R. Ohira *et al.*, in preparation.
[2] A. Noguchi *et al.*, Nat. Commun. **5**, 3868 (2014).

Poster No. 53

Cryogenic setup for quantum computing with long strings of ions

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We present our new cryogenic setup geared towards quantum computing with strings of ions containing two isotopes of Ca^+. The setup also includes a number of new technical developments. To achieve a stable magnetic field we use superconducting coils in a "self-shielding" configuration, which suppresses magnetic field fluctuations all the way down to DC. For control of multiple ions in parallel, we are working to develop a compact single ion addressing system based on an array of in-vacuum waveguides matched and imaged with no magnification to the ion positions. Ion imaging will be performed using a camera with low pixel count and FPGA-based image processing, allowing multiple ions to be imaged simultaneously with low-latency, which is essential for fast feedback. On the theoretical side, I will describe a Coulomb exchange based method for rapid cooling. Design considerations as well as results from trapping of ions in the setup will be described.

Poster No. 54

Towards co-trapping Ca^+ and BH^+

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BH^+ is a candidate for direct laser-cooling[**1**]. We report our plan on the generation BH by ablation of a Boron target in a hydrogen jet after which the BH molecules will be photoionized and trapped in an RF Paul trap also containing laser-cooled Ca^+. Our experiment progress towards the spectroscopy of sympathetically cooled BH^+ are also presented.

[1] J. H. V. Nguyen *et al.*, New J. Phys. 13, **063023** (2011).

Poster No. 55

QuantumIon: A Platform for Multi-User Remote Quantum Experiments

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Some major barriers in the use of ion traps for quantum computation and simulation are the expense of the apparatus, and the technical knowledge necessary to convert circuit-level descriptions of quantum algorithms into the laser timing pulses and associated controls. We present the design for a multi-user, 10-qubit quantum computer based on a surface trap that brings usability closer to the general research community. A novel custom control system provides users with remote control capability at various levels of abstraction: timing, gate, and circuit. The design gives the user fine-grained control of experimental parameters, along with built-in calibration, safety interlocks, advanced timing control and arbitrary pulse generation. The combination of multi-user control on a modern ion trap platform brings performance, and usability to both the experimentalist and theorist.

Poster No. 56

The $^2F_{7/2}$ state of Yb^+ as a resource for ultra-high SPAM and qudits

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The unique, low-lying F state in Yb^+ is currently employed in quantum information science almost exclusively for making clocks and optical-frequency qubits. We describe how this resource can be in conjunction with the ground state $S_{1/2}$ manifold to aid in the scaling of trapped ion quantum information science. Narrow-band optical pumping into the $^2F_{7/2}$ from one of the conventional $^2S_{1/2}$ qubit states is projected to achieve a higher state preparation and measurement (SPAM) fidelity than any other demonstrated technique. As it is based on frequency-selective optical pumping, this scheme is straightforward, does not require extreme polarization purity, frequency or intensity control, and can be implemented by any groups already using Yb^+ with very few changes to their apparatus.

Poster No. 57

Quantum Simulation with 2D Lattices of 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 and quantum chemical systems. This poster will describe progress towards the design and construction of a 2D quantum spin simulator to investigate physics currently inaccessible to 1D trapped ion systems. The effective quantum spins will be encoded within the well-isolated electronic levels of Yb-171 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. 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.

Poster No. 58

Progress towards building a programmable trapped-ion quantum simulator

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The exquisite control achievable over trapped ion qubits make the platform ideal for simulating quantum many-body systems intractable on classical computers. Here, we report on our progress towards building a trappedion quantum simulator, highlighting a novel holographic optical scheme to manipulate individual qubits. We also highlight our theoretical efforts to engineer arbitrary spin-spin interaction graphs, by manipulating spin-phonon couplings. Machine learning methods can be employed to program these spinphonon couplings individually for analog simulation of higher dimensional spin models in a linear chain of ions. Alternatively, global optical controls are capable to realize 2D spin lattices following an analog-digital hybrid protocol[**1**]. We acknowledge funding from U Waterloo, TQT (CFREF), NSERC, US ARO and Ontario Government.

[1] *npj Quantum Information* 5:32 (2019)

Poster No. 59

Doppler Cooling of $^{40}Ca^{+}$ in a Compact Penning Trap

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Penning traps operating within large 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. We have recently demonstrated Doppler laser cooling of 2D and 3D arrays of $^{40}Ca^{+}$ in a compact, reconfigurable Penning trap built with permanent magnets (N52 NdFeB). Permanent-magnet based Penning traps allow for passive ion confinement without radiofrequency micromotion, making them potentially attractive as portable frequency references. We describe a technique for characterizing the uniformity and stability of the Penning trap magnetic environment in the absence of trapped ions using neutral ^{40}Ca precursor atoms and present progress towards trapping and laser cooling $^{9}Be^{+}$.

Poster No. 60

Improving Ion Traps: Optimizing Photon Detection via Integrated Cavities and SNSPDs

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Trapped atomic ions are one of the leading contenders towards the realization of a future quantum processor. For the $^{171}Yb^{+}$ qubit, information is stored in the hyperfine levels of the ground state, and photon scattering from the dipole transition, which is only resonant with the qubit state $|1\rangle$, identifies the qubit state. Current adaptations using a high NA lens for collecting the photons have reported $\sim 4.4\%$ photon detection efficiency [**1**]. By integrating a microcavity on the order of a few hundred microns, near the trapped Ytterbium ion, the overall photon collection efficiency can improve to 55%. Furthermore, replacing typical photomultiplier tubes with near unity gain superconducting nanowire single photon detectors pushes the detection efficiency up an order of magnitude, with theoretical values of 45% achievable.

[1] S. Crain et al. arXiv:1902.04059

Poster No. 61

Ion-trap Potential Modulation as an Optical Phase Control

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Individual addressing of ion qubits has typically relied on local Rabi or transition frequency differences between ions created via electromagnetic field spatial gradients or via ion transport operations. Alternatively, it is possible to synthesize arbitrary local one-qubit gates by applying local phase differences in the driving field. Here, we implement such phase shifts on two ions co-trapped within the same potential well. By dynamically relaxing, tightening, and shifting the axial trap potential we move the ions to different phase fronts within a shared laser field. We characterize phase control of a single $^{40}Ca^{+}$ ion using the proposed scheme, simultaneously perform Ramsey experiments on two ions within a single potential well, and demonstrate one-qubit randomized benchmarking on the two ions.

Poster No. 62

Operation of MEMS-fabricated 3D ion microtraps

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Our monolithic devices have a 3D electrode geometry and contain a linear microtrap array of 1 loading and 7 operation segments. Devices are produced with high yield in a wafer-scale fabrication process. Using $^{88}Sr^{+}$, coherent spectroscopy of single ions and 2-ion strings shows confinement at the Lamb-Dicke limit. At room temperature, the device shows a motional heating rate of 2.6(2) quanta/s (axial mode at $\omega_z/2\pi = 1.05$ MHz). Experiments towards demonstration of Mølmer-Sørensen entanglement scheme are in progress; this is done via a bichromatic laser field applied to the COM mode sidebands of the $^2S_{1/2}, m_J = -1/2$ - $^2D_{5/2}, m_J = -5/2$ transition. To take advantage of the system's low motional heating rate and maximise coherence, an ultrastable Ti:sapphire laser at 674 nm (linewidth ~ 1 Hz) drives the optical qubit transition via a power- and position-stabilised beam. Additionally, passive shields and active field control minimise magnetic noise to $\leq 2 \times 10^{-6}$ G.

Poster No. 63

Trapped Ion Slow Light

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Building hybrid quantum networks will require interfacing different types of quantum systems. To demonstrate one type of hybrid platform, we present our work demonstrating slow light in a rubidium vapor using photons from a single trapped barium ion[**1**]. To overcome the large optical frequency difference between the two systems, quantum frequency conversion is performed with the photon emitted by the ion[**2**]. Using a single beam approach[**1**] we obtain tunable single photon delays up to 13.5(5) ns. This work constitutes the first demonstration of an interaction between photons emitted from a single trapped ion and neutral atoms, laying the groundwork for future ion-neutral hybrid photonic interactions.

[1] J.D. Siverns, J. Hannegan and Q. Quraishi, arXiv:1808.07928 (2018).

[2] J. D. Siverns, J.Hannegan and Q. Quraishi, Phys. Rev. Applied **11**, 014044 (2019).

[3] R. M. Camacho, M. V. Pack and J. C. Howell, Phys. Rev. A **73**, 063812 (2006).

Poster No. 64

Squeezing-based amplification of trapped ion motion

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We report fast, unitary squeezing of trapped ion motion through parametric modulation of the motional frequency, achieving 20.6(3) dB of squeezing in 7.5 μs. We use this squeezing to demonstrate phase-sensitive amplification of coherent motional displacements of a single $^{25}Mg^{+}$ ion, finding a factor of 7.3(3) enhancement in sensitivity relative to the standard quantum limit [**1**]. We also employ squeezing to enhance the speed of laser-free two-qubit geometric phase gates up to three-fold. Finally, we demonstrate a scheme for phase-insensitive amplification of a broad class of motional Hamiltonians, amplifying a laser-beam-induced sideband interaction as proof of principle. This work is supported by the NIST Quantum Information Program.

[1] S. C. Burd *et al.*, arXiv 1812.01812 (2018)

Poster No. 65

A dual-species MOTion trap

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We report on progress to create a hybrid dual-species calcium and ytterbium magneto-optical trap (MOT) superimposed onto a linear quadrupole trap. This "MOTion" trap will allow us to trap neutral atoms in the MOT, ionize them using ns-duration pulsed lasers, and trap the resulting plasma in the quadrupole trap. Driving the trap at two frequencies we will eliminate centrifugal separation inherent in simultaneous trapping of different mass ions. The primary goal of this experiment is to measure collisional momentum transfer between the Yb^{+} and Ca^{+} ions as a means of determining plasma transport properties in a strongly coupled plasma environment. Using carefully aligned probe laser beams and spatial imaging of the ion fluorescence, we anticipate being able to distinguish between the coherent ion micromotion and the thermal ion motion in the plasma.

*This research is supported by grants AFOSR FA9550-17-1-0302 and NSF-PHY-0511376.

Poster No. 66

Trapped-Ion Spin-Motion Coupling with Microwaves and a Near-Motional Oscillating Magnetic Field Gradient

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We present a new method of spin-motion coupling for trapped ions using microwaves and a magnetic field gradient oscillating close to the ions' motional frequency. We demonstrate and characterize this coupling experimentally in a surface-electrode trap that incorporates current-carrying electrodes to generate the microwave field and the oscillating magnetic field gradient. Using this method, we perform resolved-sideband cooling of a single motional mode to its ground state [**1**]. We also present initial results on entangling gates between two ions using new dynamical-decoupling techniques [**2**].

[1] R. Srinivas *et al.*, Phys. Rev. Lett. **122**, 163201 (2019).
[2] R. T. Sutherland *et al.*, New J. Phys. **21**, 033033 (2019).

Poster No. 67

Integrated Electronics for Chip-Scale Trapped-Ion Quantum Control

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Trapped-ion quantum information processors offer many advantages for achieving high-fidelity operations, but current experiments are typically composed of large components that will prohibit increasing to much higher numbers of ions. In order to achieve Moore's-law-like growth, control systems may be integrated into a single device, using technologies that can be scaled. To this end, we present ion-trap designs incorporating on-chip, low- and high-voltage CMOS electronics to generate surface-electrode control potentials without external analog voltage sources. A serial bus programs integrated digital-to-analog converter electronics, which also includes analog switches for reducing amplifier noise and a multiplexer for performing *in situ* voltage calibration. Integration of control circuits will enable future ion trap designs in which the number of electrodes makes external sources impractical.

Poster No. 68

First light from HCIs observed by the NEXT microcalorimeters

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NIST has built a new broadband X-ray spectrometer from an array of 192 individual TES (Transistion Edge Sensor) microcalorimeters designed specifically for high resolution X-ray spectroscopy of atomic transitions in highly charged ions (HCIs), spanning a spectral range from a few hundred eV to 20 keV. Commissioned recently at the NIST EBIT (electron beam ion trap), this array of time-resolved photon-counting X-ray TES is dubbed the acryonym “NEXT”. We present the first NEXT observations of X-ray emissions from various ion species created in the NIST EBIT [**1**], which serve to illustrate its capabilities. Preliminary measurements for testing atomic theory and other potential applications are also discussed.

[1] P. Szypryt, G. C. O’Neil, E. Takacs, J. N. Tan, S. W. Buechele, A. S. Naing, D. A. Bennet, W. B. Doriese, M. Durkin, J. W. Fowler, J. D. Gard, G. C. Hilton, K. M. Morgan, C. D. Reintsema, D. R. Schmidt, D. S. Swetz, J. N. Ullom, and Yu. Ralchenko, in preparation.

Poster No. 69

Entangling gates that are simultaneously insensitive to qubit and motional decoherence

R. T. Sutherland[1], R. Srinivas[2,3], S. C. Burd[2,3], D. Leibfried[2], A. C. Wilson[2], D. J. Wineland[2,3,4], D. T. C. Allcock[2,3,4], D. H. Slichter[2], and S. B. Libby[1]

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Laser-free trapped-ion entangling gates are a promising technique for quantum information processing, but gate fidelities are currently limited by qubit and motional decoherence. Here, we propose a laser-free gate that is simultaneously resilient to both types of decoherence. This is achieved through "intrinsic" dynamical decoupling for the qubit, and through origin-centered phase space trajectories for the motion. Crucially, our gate does not require additional control fields.

Poster No. 70

Control of ion configuration in on-chip ion traps

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We present two types of on-chip ion traps which realize distinctive ion configurations. One is an ion string with equal spacing, the other is parallel ion strings. The former is being developed for portable multi-ion optical clocks. The specification of such optical clock is discussed. The spacing equality of an ion string consisting of 17 calcium ions was improved by feedback of the difference between the ideal and measured trap potential to DC electrodes. In addition, a trap for an isospaced ion string consisting of one hundred ions is designed, which has a possibility of application to a superradiant laser. The latter, parallel ion strings, performed with on-chip ion traps which enable both single-well and double-well operation in the radial direction[**1**]. This configuration is useful for emulation of the nanofriction model..

[1] U. Tanaka *et al.*, J. Phys. B 47, **035301** (2014)

Poster No. 71

Improved ion transport and detection in a surface-electrode trap

S. L. Todaro[1], V. B. Verma[1], R. P Mirin[1], S. W. Nam[1], D. J. Wineland[1], A. C. Wilson[1], D. Leibfried[1], D. H. Slichter[1]

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We seek to improve fast transport and implement trap-integrated state readout in in a cryogenic surface-electrode trap with an integrated superconducting nanowire single-photon detector (SNSPD)[**1**]. Trap-integrated fluorescence detection promises reduced complexity and improved scalability relative to bulk collection optics. We report readout of a trapped ion qubit using this SNSPD, as well as the detector's impact on the ion's motional heating. We also investigate ion transport. In previous experiments this has mostly been performed adiabatically in order to reduce motional excitation, with durations much longer than typical gate operations. We aim towards multi-zone ion transport carried out on timescales comparable to those of gate operations and with minimal net motional excitation. This research is supported by IARPA and the NIST Quantum Information Program.

[1] D. H. Slichter em et al., Opt. Express **24**, 2705 (2017)

Poster No. 72

Towards Continuous Variables Quantum Computing with Trapped Ions

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Here we report on the recent progress to explore the continuous variable approach to quantum computations with a single trapped 171Yb+ ion. By applying spin dependent force at the frequency corresponding to a difference between the frequencies of two modes of motion, we implement a gate which swap the populations of the modes conditioned on the internal state of the ion. We utilize this gate in an efficient scheme to produce maximally entangled (NOON) states of up to 4 phonons. Also, we devise and implement the algorithm to perform a single-shot measurement of the Wigner function of the motional state and also a measurement of the overlap between quantum states belonging to two different modes.

Poster No. 73

Ablation Loading and Co-Trapping of $^{174}Yb^{+}$ and $^{138}Ba^{+}$ in a Surface Trap

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Quantum computing experiments with trapped ions are becoming increasingly complex, and while the loss of coherence of the internal state is negligible for trapped ions, the heating experienced by the ion chain will likely become a limit on the fidelity of logic gates which use modes of motion as the logic bus allowing for two-qubit gates. In order to cool the motional modes of the ion chain without introducing resonant scattering effects, chains comprised of two different species are considered prime candidates. Here, we present a system in which we have used a Nd:YAG ablation laser to isotope-selectively trap both ^{174}Yb and ^{138}Ba. We present a time-dependent fluorescence characterization of the neutral Yb, as well as an analysis of the loading rate and efficiency of both species. Additionally, we present the characterization of an extremely compact novel room-temperature surface trap system.

Poster No. 74

Probing New Bosons via Isotope Shift Spectroscopy of Yb

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Hypothetical new boson-to-matter coupling via isotope shift (IS) spectroscopy [**1, 2**] is studied in particular for Yb. Bounds on new-boson couplings from IS measurement are examined from relativistic wavefuntions of Yb^+ and neutral Yb calculated with GRASP2018 [**3**]. Higher-order corrections in mass and field shifts are estimated, which limit ultimate sensitivity of Yb as the probe for the new interaction. Improving such limits by generalizing King plot for more than two transitions [**1**] is investigated. Measurement of ISs in Yb^+ is underway for clock transitions, $^2S_{1/2} \to {}^2D_{3/2}$ and $^2S_{1/2} \to {}^2D_{5/2}$ at sub-kHz precision [**4**].

[1] K. Mikami, M. Tanaka, and Y. Yamamoto, Eur. Phys. J. C **77** (2017)
[2] J. C. Berengut *et al.*, Phys. Rev. Lett. **120** (2018)
[3] C. F. Fischer *et al.*, Comput. Phys. Commun., **237** (2019)
[4] I. Counts, J. Hur, H. Jeon, W. Jhe, and V. Vuletić (unpublished)

Poster No. 75

A single ion-qubit with long coherence time

Pengfei Wang[1], Chun-Yang Luan[1], Mu Qiao[1], Mark Um[1], Junhua Zhang[1], Ye Wang[1], Kihwan Kim[1]

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The coherence time of a single $^{171}Yb^{+}$ ion-qubit over 600 s has been reported with sympathetic cooling by a $^{138}Ba^{+}$ ion and optimized dynamical decoupling-pulses in an ambient magnetic field condition[**1**]. However, it was not clear what prohibits further enhancement. Here, we experimentally investigate the limiting factors and enhance the coherence time to more than 2000 s. In our system, we find that ambient magnetic-field noise and phase noise of the local oscillator are main sources for decoherence. To suppress field fluctuation, we enclose our vacuum system with a two-layer μ-metal magnetic-shielding and use a permanent magnets to produce stable field. In this way, we observe the coherence time of field-sensitive qubit is increased to more than 30 ms. For the reference of the local oscillator, we use a crystal oscillator, which has one order of magnitude smaller Allan deviation than our previous Rb clock at 1 s. After such improvements, we clearly observe the coherence time of clock state of $^{171}Yb^{+}$ ion is increased more than 3 times.

[1] Wang Y et al. Nature Photonics, 2017, 11(10): 646.

Poster No. 76

A monolithic parabolic-mirror ion trap for enhancing photon collection

Zhao Wang[1], Bengran Wang[1], Qingling Ma[1],Xingxing Rao[1], Pengfei Lu[1], Yuanyuan Zhao[1], Feng Zhu[1], and Le Luo[1]

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Trapped ions are one of the most prominent systems for scalable quantum computing as well as quantum networking. For the networking purpose, enhancing the collection efficiency of spontaneously-emitted photons has kept as the most challenge problem for many-years. In this presentation, we propose a practical design of using a monolithic parabolic-mirror ion trap, in which the saddle point of the trapping potential overlaps with the focal point of the mirror with high precision. The numerical simulation indicates that this setup can collect up to 94% of the solid angle of the emitted photons. Furthermore, the tight focusing geometry of this parabolic-mirror trap provides an optical trapping potential to realize long-time optically-trapped ion with rf-potential off, and thus eliminate the micromotion of the ion for high-fidelity implementation of type-I photon mediated ion-ion entanglement[**1**]

[1] D. J. Wineland *et al.*, J. Res. Natl. Inst. Stand. Technol. 103, **259** (1998)

Poster No. 77

Coherent motional control of calcium ions in a Penning trap

S. C. Webster[1], O. Corfield[1], J. Heinrich[1], C. Lee[1], P. Hrmo[1], V. Jarlaud[1], M. K. Joshi[1], J. Lishman[1], F. Mintert[1], and R. C. Thompson[1]

[1] Department of Physics, Imperial College London, London SW7 2AZ, UK

While three-dimensional sub-Doppler cooling of ions in a Paul trap has become routine, such cooling has not been realised in a Penning trap. We demonstrate cooling of both the modified cyclotron and magnetron modes of single ions. Sideband cooling of ion crystals becomes challenging when ions are weakly confined and we demonstrate the cooling of axial modes of two ions for both axial and planar crystal configurations [**1, 2**]. We will also present preliminary data in preparing superpositions of different motional states to investigate higher order interference fringes involving more than two levels, and our progress in building a linear Paul trap for further investigating the quantum dynamics of weakly trapped ions.

[1] G. Stutter *et al.*, J. Mod. Opt., **65**, 549 (2018)
[2] M. K. Joshi *et al.* Phys. Rev. A **99**, 013423 (2019)

Poster No. 78

Rotation Sensing with a Trapped Ion

A. D. West[1], R. Putnam[1], W. C. Campbell[1], and P. S. Hamilton[1]

[1] University of California, Los Angeles, CA 90095, USA

We report work towards precision rotation sensing with a trapped $^{138}\mathrm{Ba}^+$ ion [**1**], building on the recently developed spin-dependent kick (SDK) technique [**2**] with a novel scheme based on a Zeeman qubit. We drive Raman transitions in the $S_{1/2}$ ground state with picosecond laser pulses. With this new spin-motion entanglement scheme, we are working towards free-oscillation interferometry with trapped ions and characterization of associated systematic effects [**3**]. Anticipated shot-noise-limited sensing precision is competitive with commercial devices. SDKs in $^{138}\mathrm{Ba}^+$ may also provide a versatile technique for achieving large momentum transfer that could be broadly applicable to matter-wave interferometry and ultrafast multi-qubit gates [**4**].

[1] W. C. Campbell and P. Hamilton, J. Phys. B **50**, 064002 (2017)
[2] J. Mizrahi et al., Phys. Rev. Lett. **110**, 203001 (2013)
[3] A. D. West, arXiv:1904.12707 (2019)
[4] J. D. Wong-Campos et al., Phys. Rev. Lett. **119**, 230501 (2017)

Poster No. 79

Realistic high-fidelity protocols for qudit-based quantum computing

B. White[1], P. Low[1], A. Cox[1], M. Day[1], and C. Senko[1]

[1]Institute for Quantum Computing, University of Waterloo , Waterloo, Canada N2L3G1

We present on the feasibility of implementing quantum information processing using multi-level qudits encoded within trapped ions. We describe protocols for how current technology may be used to implement high-fidelity state preparation, measurement, and single- and two-qudit gates in a trapped ion framework. A scalable measurement scheme using rapid adiabatic passage to shelve to a meta-stable state is presented, along with a discussion of single-qudit gate implementation, and a practical method for implementing two-qudit entangling gates (mediated by collective phonon modes) using a geometric phase approach. From our error estimations, we can achieve better than 99% fidelity for three-level qudit operations and measurement, exceeding the estimated surface-code error correction threshold. We anticipate that further improvements to the measurement technique and the qudit manipulations could be made to push these fidelities higher.

Poster No. 80

Towards Sympathetic Cooling of Single Protons and Antiprotons

M. Wiesinger[1,2], M. Bohman[1,2], C. Smorra[2], and BASE collaboration

[1]Max-Planck-Institut fuer Kernphysik, MPG, Germany
[2]Ulmer Fundamental Symmetries Laboratory, RIKEN, Japan

We, the BASE collaboration, perform most precise tests of the CPT symmetry in the baryon sector by measurements on the proton and antiproton.

Our recent 300 ppt measurement of the proton magnetic moment at the proton g-factor experiment in Mainz is limited by statistics. The reason is that the current use of sub-thermal cooling of a single proton by a resistive method is extremely time-consuming and leads to cycle times of hours.

To overcome this limitation sympathetic cooling by laser-cooled Be^+ ions in a common-end-cap Penning trap is being developed: The method not only promises to produce (anti)protons with mK temperatures within tens of seconds but also achieves separation of the cooled and the refrigerator ion.

We present the current setup of the proton g-factor experiment and report on the status and recent achievements, such as in-trap detection of fluorescence photons using SiPMs at 4K, located 12mm from the Be^+ ion cloud.

Poster No. 81

Phonon pair creation by tearing apart quantum vacuum fluctuations

M. Wittemer[1], F. Hakelberg[1], P. Kiefer[1], J.-P. Schröder[1], C. Fey[2], R. Schützhold[3], U. Warring[1], and T. Schaetz[1]

[1]University of Freiburg
[2]University of Hamburg
[3]University of Duisburg-Essen, Helmholtz-Zentrum Dresden-Rossendorf, and TU Dresden, Germany

We switch the trapping field of two ions sufficiently fast to tear apart quantum vacuum fluctuations and, thereby, create squeezed states of motion [**1**]. This process can be interpreted as an experimental analog to the particle pair creation during a cosmic inflation in the early universe [**2**] and is accompanied by the formation of entanglement in the ions' motional degree of freedom [**3**]. Hence, our platform allows studying the causal connections of squeezing, pair creation, and entanglement and might permit to cross-fertilize between concepts in cosmology and applications of quantum information processing.

[1] M. Wittemer *et al.*, arXiv:1903.05523 (2019)
[2] R. Schützhold *et al.*, PRL **99**, 201301 (2007)
[3] C. Fey *et al.*, PRA **98**, 033407 (2018)

Poster No. 82

Cryogenic Performance of Microfabricated Surface Ion Traps

C. G. Yale[1], C. W. Hogle[1], and P. Maunz[1]

[1]Sandia National Laboratories, Albuquerque, NM 87185

Microfabricated surface electrode ion traps offer a route to scalable quantum information processing, but anomalous heating limits gate fidelities, while ion chain lifetimes are hampered by background gas collisions. Here, we investigate the performance of Sandia's microfabricated traps in a cryogenic environment in an attempt to decrease heating rates and background pressure. We demonstrate ablation loading of ions and the use of an internal toroidal circuit board resonator. We then measure low background gas collision rates in a double well potential and observe hours-long ion chain lifetimes. However, we measure heating rates comparable or worse than seen at room temperature and investigate potential sources of this heating, including surface issues and background pressure. [**1**]

[1] SNL is managed and operated by NTESS, LLC, a subsidiary of Honeywell International, Inc., for the US DOE NNSA under contract DE-NA0003525. This research was funded by IARPA. The views expressed here do not necessarily represent the views of the DOE, IARPA, or the U.S. Government.

Poster No. 83

Entanglement with microwave near-fields in a surface-electrode trap

G. Zarantonello[1,2], H. Hahn,[1,2], J. Morgner[1], A. Bautista-Salvador[1,2] and C. Ospelkaus[1,2]

[1]Institut für Quantenoptik, Leibniz Universität Hannover, Welfengarten 1, 30167 Hannover
[2]PTB, Bundesallee 100, 38116 Braunschweig

Microwave driven quantum operations represent an alternative to the commonly used laser approach. In the case of surface-electrode traps microwave conductors can easily be integrated in the trap structures to produce the desired oscillatory near-field pattern and perform the multi-qubit operations necessary for quantum computation [**1**]. This poster reports the results from our experiment where we have achieved a two-qubit gate fidelity above 98% in $^{9}Be^{+}$ [**2**]. The main error source is the ion's radial mode stability. The current efforts to reduce the impact of this error source will also be presented.

[1] C. Ospelkaus *et al.*, Phys. Rev. Lett. **101** 090502 (2008)
[2] H. Hahn *et al.*, arXiv:1902.07028 (2019)

Poster No. 84

Sub-microsecond Quantum Gate in Trapped Ions by Rydberg Interactions

C. Zhang[1], F. Pokorny[1], G. Higgins[1], W. Li[2], I. Lesanovsky[2], and M. Hennrich[1]

[1]Department of Physics, Stockholm University, 10691 Stockholm, Sweden
[2]School of Physics and Astronomy, University of Nottingham, Nottingham, NG7 2RD, United Kingdom

Trapped Rydberg ions [**1**] are a novel approach for quantum information processing. By combining the high degree of control of trapped ion systems with the strong dipole-dipole interactions of Rydberg atoms, fast entanglement gates may be realized in large ion crystals. In our experiment, we excite trapped $^{88}Sr^{+}$ ions to Rydberg states. We have observed strong interactions between microwave-dressed Rydberg ions for the first time. Recently, we realized a 700 *ns* controlled phase gate in a two ion crystal and entangled the ions with over 80% fidelity. This fast gate doesn't rely on ion motion, so it could be applied in long ion crystals. These are fundamental steps towards a trapped Rydberg ion quantum computer or simulator.

[1] M. Müller, *et al*, New J. Phys. 10, **093009** (2008)

Poster No. 85

Control System Infrastructure and Execution Pipeline for Trapped Ions Quantum Computing

B. Zhang[1], S. Crain[1], Y. Wang[1], S. Huang[1], M. Li[1], J. Kim[1], and K. Brown[1]

[1]Duke University , Durham, NC 27705

High-fidelity quantum operations have been demonstrated in small ion chains but manipulating multiple ion qubits coherently to execute arbitrary quantum circuits remains challenging. Our goal is to develop a scalable control system which translates arbitrary quantum circuits into experimental pulse signals across a quantum register of ions. Here, we present a control system based on Advanced Real-Time Infrastructure for Quantum physics (ARTIQ) for conducting a set of universal quantum gates with an ion chain in a surface trap. Also, we propose robust two-qubit gate solutions that translate continuous frequency modulated gates [**1**] in to discrete frequency pulses compatible with direct digital synthesizers (DDS).

[1] P. H. Leung *et al.*, Physical review letters 120.2 (2018): 020501.

Poster No. 86

Error-Mitigated Quantum Gates Exceeding Physical Fidelities in a Trapped-Ion System

Shuaining Zhang[1], Yao Lu[1], Kuan Zhang[2,1], Wentao Chen[1], Ying Li[3], Jing-Ning Zhang[1], and Kihwan Kim[1]

[1]Center for Quantum Information, Tsinghua University, Beijing 100084, China
[2]Huazhong University of Science and Technology, Wuhan 430074, China
[3]Graduate School of China Academy of Engineering Physics, Beijing 100193, China

Various quantum applications can be reduced to estimating expectation values, which are inevitably deviated by operational and environmental errors. To alleviate the detrimental effects of errors, quantum error mitigation techniques have been proposed, which require no additional qubit resources. We benchmark the performance of a quantum error mitigation technique based on probabilistic error cancellation in a trapped-ion system. Our results clearly show that effective gate fidelities exceed physical fidelities. The error rates are effectively reduced from $(1.10 \pm 0.12) \times 10^{-3}$ to $(1.44 \pm 5.28) \times 10^{-5}$ and from $(0.99 \pm 0.06) \times 10^{-2}$ to $(0.96 \pm 0.10) \times 10^{-3}$ for single- and two-qubit gates. Our demonstration opens up the possibility of implementing high-fidelity computations on a near-term noisy quantum device.

Poster No. 87

Design and fabrication of a surface trap for trapped ion quantum computing

W.-D. Zhao[1], Y. Jiang[1], Z.-C. Mao[1], Q.-X. Mei[1], Z.-C. Zhou[1], L. He[1], and L.-M. Duan[1]

[1]Center for Quantum Information, Institute for Interdisciplinary Information Sciences, Tsinghua University, Beijing 100084, China

In our lab, we focus on constructing scalable micro ion trap systems for quantum computing and simulation. We are building a micro-fabricated surface trap system which involves trap potential simulation, ion dynamics simulation, the design and fabrication of surface chip trap and other auxiliary setups. We also estimate the heating rate and circuit characters of surface trap experimentally and theoretically. Recently, we finished several versions of surface chip traps which can realize different trap potentials to tune the spacing between the ions. The chip trap was fabricated through the growth of metal coating over a semiconductor substrate with fine structure ($\sim \mu$m). We also built a segmented blade trap system and work on individual ion addressing and laser frequency stabilization.

In the future, we will fabricate more complicated structure on the chip which can give us the capability to transfer quantum information between remote ion traps.

Poster No. 88

Current Status of the JILA eEDM Experiment

K. B. Ng[1], W. B. Cairncross[1], T. S. Roussy[1], T. Grogan[1], Y. Zhou[1], Y. Shagam[1], M. Pettine[1], A. Vigil[1], J. Ye[1], and E. A. Cornell[1]

[1] JILA, NIST and University of Colorado, and Department of Physics, University of Colorado, Boulder CO 80309-0440, USA

A measurement of the electric dipole moment of the electron (eEDM, d_e) provides a direct test of theories beyond the Standard Model to provide insight into new physics like baryonic asymmetry and dark matter. Molecular ions like HfF^+ and ThF^+ are sensitive to the eEDM, and allow for excellent rejection of systematics through the ${}^3\Delta_1$ science state. The JILA eEDM experiment takes advantage of the large effective electric field and long coherence times of these trapped ions for the probe of the eEDM.

In the first generation JILA eEDM experiment, we obtained an upper bound of $|d_e| < 1.3 \times 10^{-28} e\,\text{cm}$ (90% confidence) with trapped HfF^+[**1**]. Herein, I present an overview of the ongoing improvements to the experiment.

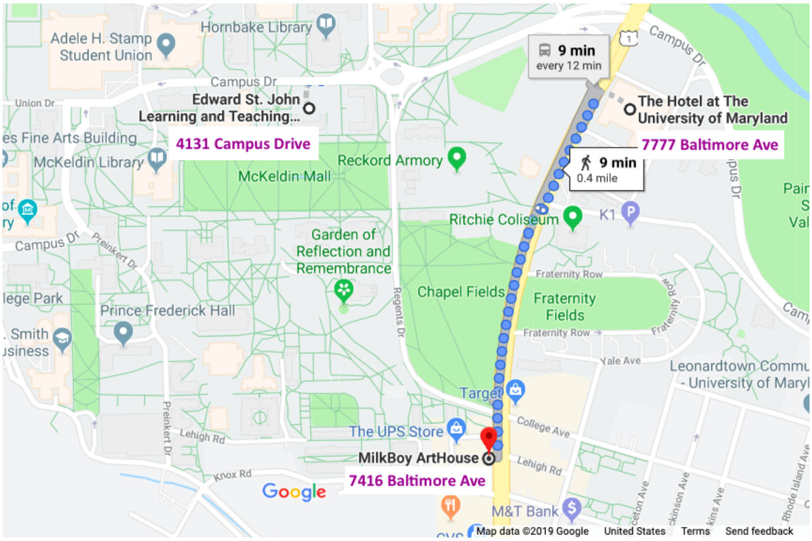
[1] W. B. Cairncross, et. al., Physical Review Letters, **119**, 153001 (2017).

MilkBoy ArtHouse Event

“Trapped Ions in Industry Form”

Tuesday, July 23, 19:00–21:00
MilkBoy ArtHouse, 7416 Baltimore Ave.

Moderated by Chris Monroe, this event will feature a panel of companies which are developing ion traps for quantum information or other applications. Refreshments will be provided.



Excursion

Scheduled for the afternoon of Wednesday, July 24th. Buses will be leaving immediately after lunch and will drop off at the Washington National Mall. Nearby attractions include (but are not limited to):

<u>The Monuments</u>: The iconic Washington Monument, World War II Memorial, Lincoln Memorial, Jefferson Memorial, Franklin Delano Roosevelt Memorial and the Martin Luther King, Jr. Memorial are all within easy walking distance from the Mall.

The White House and the United States Capitol are both next to the Mall. The Capitol Visitor Center is open to the public and closes at 4:30 p.m.

<u>Museums</u>: The Mall is home to many different museums offering a wide selection of subject matters and interests. The Air & Space Museum, the Museum of Natural History and the National Gallery of Art are just a few! Check the opening hours before you go: most museums close at 5 or 5:30 pm.

Bus Information

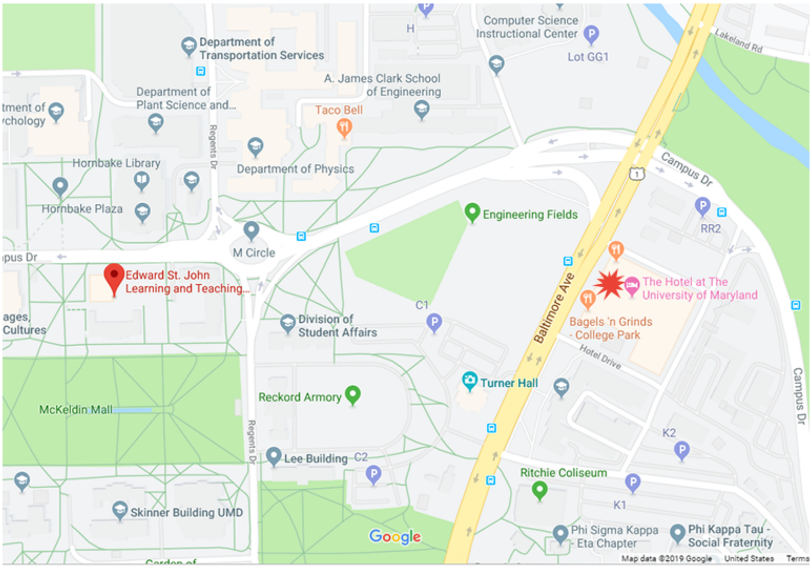
Buses are located at the Adele H. Stamp Student Union slip on Campus Drive, across from the Stamp Studion Union and Nyumburu Cultural Center. Buses will begin boarding at 1:15 pm for a 1:30 pm departure to Washington, D.C. Buses will drop off at the Lincoln Memorial (Henry Bacon Drive NW). For the return trip, buses will begin boarding again at 7:15pm at the Lincoln Memorial for a 7:30pm departure to The Hotel, 7777 Baltimore Ave.

Participants are free to stay out later and return to College Park by Metro or taxi.

Conference Dinner

Thursday, July 25, 18:30–20:30
The Crossland Ballroom at The Hotel
https://www.thehotelumd.com

*Vegetarians, please bring the ticket you received at registration.



Lab Tours

Tours will visit labs of the four ion trap groups on campus (Monroe, Linke, Quraishi, and Britton), and will leave from ESJ after lunch on Friday 07/26.

Sign-up sheets will be available at the conference desk throughout the week.

Technical Exhibit

The technical exhibit will run Monday–Thursday in the conference venue. The following companies are represented:

ColdQuanta	https://www.coldquanta.com/
Covesion	https://www.covesion.com/
IonQ	https://ionq.co/
Joint Quantum Institute	https://jqi.umd.edu/
M-Squared Lasers Limited	http://www.m2lasers.com/
NKT Photonics	https://www.nktphotonics.com/
Stable Laser Systems	http://www.stablelasers.com/
Teledyne Princeton Instruments	https://www.princetoninstruments.com/
TOPTICA Photonics	https://www.toptica.com/
Vescent Photonics	https://www.vescent.com/
Vexlum	https://www.vexlum.com/

Organization

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NACTI 2019 Operations

Samantha Suplee (UMD)	ssuplee@umd.edu

^{19}NACTI^{+}	Mon, July 22	Tue, July 23	Wed, July 24	Thu, July 25	Fri, July 26
0900-0930	Welcome	Safronova (UD)	Ballance (Oxford)	Meir (Basel)	Maunz (Sandia)
0930-1000	Monroe (UMD)	v.d. Wense (JILA/LMU)	Leibfried (NIST)	Mills (UCLA)	Chiaverini (MIT-LL)
1000-1030	Affolter (NIST)	King (PTB)	Mehta (ETH)	Odom (Northwestern)	Hite (NIST)
1030-1115	Break	Break	Break	Break	Break
1115-1145	Megidish (Berkeley)	Burt (JPL)	Campbell (UCLA)	Saraladevi (Duke)	Kim (Duke)
1145-1215	Islam (Perimeter)	Brewer (NIST)	Senko (Perimeter)	Zhou (JILA)	Linke (UMD)
1215-1245	Lunch	Lunch	Lunch	Lunch	Lunch
1245-1315					
1315-1345			Excursion to DC		
1345-1415	Northup (Innsbruck)	Blatt (Innsbruck)		Neyenhuis (Honeywell)	Lab Tours
1415-1445	Quraishi (ARL)	Akerman (Weizman)		Mizrahi (IonQ)	
1445-1515	Soderberg (AFRL)	Schmidt-Kaler (Mainz)		hot topics	
1515-1600	Break	Break		Break	
1600-1630	hot topics	Poster session I		Poster session II	
1630-1700	hot topics				
1700-1730					
1730-1800					
1800-1830					
1830-1900				Conference Dinner	
1900-1930	Artiq Discussion	MilkBoy Arthouse			
1930-			bus return		