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1 Talk Abstracts

Precision measurements on a single trapped Be$^+$ ion

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Precision laser spectroscopy of transitions in simple atoms can be used as a stringent test of many-body QED calculations, or to extract subtle information about internal nuclear structure [1]. ^{9}Be$^+$ is a three electron ion which has been the focus of study in ion trap and high energy beam experiments dating back several decades and is widely used in quantum information processing experiments. Here, we present the first frequency comb-based measurements of the D-lines in ^{9}Be$^+$ using a single trapped ion [2]. The systematic uncertainty has been reduced by an order of magnitude, compared to previous work, which helps to resolve a 7σ discrepancy between the most recent ion beam and ion trap-based experiments [1]. A framework to account for systematic effects such as photon recoil heating and quantum interference is described. The first experimental measurement of the unresolved $^2P_{3/2}$ hyperfine splittings is also reported, which helped to uncover a long-standing sign error in the theoretical prediction of the $^2P_{3/2}$ electric quadrupole hyperfine constant [3]. Similar measurements on rare isotopes ^{7,10}Be$^+$ are planned using the techniques developed for ^{9}Be$^+$. A comparison of the fine structure splitting across the isotope chain can eventualy be used extract relative nuclear charge radii. Furthermore, microwave frequency Ramsey spectroscopy of the ground state hyperfine splitting of isotopes 7 and 9 can be used to extract the effective nuclear Zemach radii.

[1] W. Nörtershäuser, W. *et al.*, Phys. Rev. Lett. **102**, 062503 (2015).

[2] D. M. Fairbank, A. L. Banducci, R. W. Gunkelman, J. B. VanArsdale, M. L. Vildibill, and S. M. Brewer, Phys. Rev. Lett. **131**, 093001 (2023).

[3] D. M. Fairbank, A. L. Banducci, R. W. Gunkelman, J. B. VanArsdale, and S. M. Brewer, Phys. Rev. A **109**, 012809 (2024).

Simulating a conical intersection with a trapped ion quantum computer

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Conical intersections often control the reaction products of photochemical processes and occur when two electronic potential energy surfaces intersect. Theory predicts that the conical intersection will result in a geometric phase for a wavepacket on the ground potential energy surface, and although conical intersections have been observed experimentally, the geometric phase has not been directly observed in a molecular system. Here we use a trapped atomic ion system to perform a quantum simulation of a conical intersection. The ion's internal state serves as the electronic state, and the motion of the atomic nuclei is encoded into the motion of the ions. The simulated electronic potential is constructed by applying state-dependent optical forces to the ion. We experimentally observe a clear manifestation of the geometric phase using adiabatic state preparation followed by motional state measurement [1]. Our experiment shows the advantage of combining spin and motion degrees for quantum simulation of chemical reactions. We conclude with a discussion of future simulation directions [2].

[1] J. Whitlow *et al.*, Nature Chemistry **15**, 1509 (2023)

[2] M. Kang *et al.*, Nature Reviews Chemistry **8**, 340 (2024)

Quantum simulations and parametric amplification in a Penning trap

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The primary focuses of the NIST Penning trap experiment are quantum sensing of weak motional excitations and quantum simulations, both using hundreds of ions. Both of these applications can benefit from the use of parametric amplification, which squeezes the motion of the ions, improving the sensitivity to small displacements and enhancing spin-dependent forces without increasing errors due to spontaneous emission. In this talk, I will summarize results demonstrating parametric amplification, which we expect to improve our sensitivity for measuring weak motional excitations by 10 dB [1]. I will then discuss preliminary work toward a quantum simulation of a dynamical phase transition in the Dicke model, as proposed in [2]. Finally, I will conclude by highlighting planned future projects, including the use of three-dimensional crystals for quantum sensing and simulation and individual addressing of ions in the rotating crystal formed in the Penning trap.

[1] M. Affolter, W. Ge, B. Bullock, S. C. Burd, K. A. Gilmore, J. F. Lilieholm, A. L. Carter, and J. J. Bollinger, Phys. Rev. A **107**, 032425 (2023).

[2] R. Lewis Swan, S. R. Muleady, D. Barbarena, J. J. Bollinger, and A. M. Rey, Phys. Rev. Research **3**, L022020 (2021).

Systematic-free limit on new light scalar bosons via isotpe shift spectroscopy in Ca$^+$

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High precision isotope-shift spectroscopy on narrow optical transitions holds the promise to break new ground in the search for physics beyond the Standard Model (BSM) in intermediate mass ranges ($\lesssim$ 100 MeV). Such measurements may be combined to form a King Plot in which nonlinearities could represent the signature of "fifth-force" electron-neutron couplings. However, violations of King's Linearity can and do also arise from higher-order effects within the Standard Model. It is thus desirable to make measurements in a variety of atomic systems, particularly those with minimal SM sources of nonlinearity, to unambiguously set constraints on BSM effects.

Here we present measurements of isotope shifts amongst four nuclear-spin-zero isotopes of Ca$^+$ on both $S \to D$ electric-quadrupole transitions, reaching Hz-level precision, and generate a King plot which is consistent with linearity at below the part-per-billion level. This linear result, which is free of nuclear systematics, improves on the previous best systematic-free measurement by a factor of 3.

Advancements in Trapped-Ion Quantum Computing: Novel Cooling Techniques and Cryogenic Chamber Design

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Ion cooling currently represents a significant runtime bottleneck in the trapped-ion quantum charge-coupled device (QCCD) architecture. In this talk, I will focus on two approaches for cooling ions close to the motional ground state, both of which could have a dramatic impact on algorithm run times. The first approach, called exchange cooling, introduces a bank of "coolant" ions which are repeatedly laser cooled. A computational ion can then be cooled by transporting a coolant ion into its proximity. Unlike sympathetic cooling, a standard method in the field, exchange cooling does not require trapping of two different atomic species. The second approach, dark-resonance cooling, leverages features of electromagnetically-induced transparency within the Doppler cooling spectrum. Simultaneous cooling of both axial and radial modes of a single ion to below one quantum, with 1/e time constants of less than 100 μs, is achieved. To conclude, I will briefly describe a new cryogenic vacuum chamber for ion-trapping experiments aimed at improving beam-pointing stability, shielding from magnetic-field fluctuations, and detection efficiency.

A Site-Resolved 2D Quantum Simulator with Hundreds of Trapped Ions

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We report the stable trapping of 512 ions in a 2D Wigner crystal and the sideband cooling of their transverse motion. We demonstrate the quantum simulation of long-range quantum Ising models with tunable coupling strengths and patterns, with or without frustration, using 300 ions. Enabled by the site resolution in the single-shot measurement, we observe rich spatial correlation patterns in the quasi-adiabatically prepared ground states, which allows us to verify quantum simulation results by comparing with the calculated collective phonon modes and with classical simulated annealing. We further probe the quench dynamics of the Ising model in a transverse field to demonstrate quantum sampling tasks. Our work paves the way for simulating classically intractable quantum dynamics and for running NISQ algorithms using 2D ion trap quantum simulators.

3D-Printed Micro Ion Trap Technology for Scalable Quantum Information Processing

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Modern trapped-ion quantum information processing experiments usually rely on photo-lithographic techniques to miniaturize the traps and meet scalability requirements. Using photolithography, it is challenging to fabricate the complex three-dimensional electrode structures required for optimal confinement. Here we address these limitations by adopting a high-resolution 3D printing technology based on two-photon polymerization supporting fabrication of large arrays of high-performance miniaturized 3D traps. We show that 3D-printed ion traps combine the advantages of traditionally machined 3D traps with the miniaturization provided by photolithography by confining single calcium ions in a small 3D-printed ion trap with radial trap frequencies ranging from 2 MHz to 24 MHz. The tight confinement eases ion cooling requirements and allows us to demonstrate high-fidelity coherent operations on an optical qubit after only Doppler cooling. With 3D printing technology, the design freedom is drastically expanded without sacrificing scalability and precision so that ion trap geometries can be optimized for higher performance and better functionality.

The authors acknowledge Clemens Matthiesen's inspiration at the start of the project and James Oakdale for printing the first demonstration objects. The authors would also like to acknowledge Nicole Greene for the help on chamber assembly, Wei-Ting Chen and Sumanta Khan for the useful guidance on the measurements. This work is supported by the UC Multicampus-National Lab Collaborative Research and Training under Award No. LFR-20-653698 and the Noyce Foundation. Part of this work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344 and was supported by the LLNL-LDRD Program under Project No. 23-ERD-021, as well as by the Noyce initiative. AJ acknowledges the support of ONR Grant No. N00014-21-1-2597.

Quantum logic spectroscopy of a single $\mathbf{H_2^+}$ molecular ion

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I will present our latest results, implementing pure quantum state preparation, coherent manipulation, and non-destructive state readout of a single hydrogen molecular ion H_2^+ using quantum logic spectroscopy. We trap a single H_2^+ molecule together with a single beryllium ion using a cryogenic Paul trap apparatus, achieving trapping lifetimes of 11h and ground-state cooling of the shared axial motion [1]. We utilize helium buffer-gas cooling to prepare the lowest rovibrational state of ortho-H_2^+ (rotation $N = 1$, vibration $\nu = 0$). We combine this with quantum-logic operations between the two ions for preparation of single hyperfine states and non-destructive readout, demonstrating Rabi flopping on several hyperfine transitions.

[1] N. Schwegler, D. Holzapfel, M. Stadler, A. Mitjans, I. Sergachev, J. P. Home, and D. Kienzler, Phys. Rev. Lett. **131**, 133003 (2023)

Ions for transportable optical clocks

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A constellation of optical clocks in space would open up possibilities for fundamental physics research. To realize optical clocks on many satellites we must have low-power, small, and robust systems and not bespoke clocks, otherwise the cost would be astronomical. To meet these needs a trapped ion clock with integrated photonics is very appealing. We are working to lower the requirements for integrated photonics by using transitions in the radium ion that only require IR light. To realize such a clock we need nuclear spin and for this we are working with the radium 225 isotope which has nuclear spin $I = 1/2$. We have recently laser cooled radium-225 and measured the ion's hyperfine structure. Despite radium-225's 15 day half-life we have demonstrated an atomic source that is compatible with decades of operation in space. We have realized an optical clock with radium-226 and are working towards a clock with radium-225.

A high-accuracy $^{115}\mathrm{In}^+/^{172}\mathrm{Yb}^+$ Coulomb crystal optical clock with $6 \times 16^{-16}/\sqrt{t}$ instability

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Mixed-species Coulomb crystal operation can reduce both statistical and systematic uncertainties in optical clocks. Increased clock ion numbers provide a lower quantum projection noise limited instability and are the prerequisite for various advanced interrogation schemes, while auxiliary ions can be used for sympathetic cooling and systematic shift characterization.

We operate a clock based on a linear chain of $^{115}\mathrm{In}^+$ (clock) and $^{172}\mathrm{Yb}^+$ (auxiliary) ions, which we have identified as a favorable system for high-accuracy multi-clock-ion operation [1], capable of reaching a fractional systematic uncertainty below 1×10^{-19} [2].

With an evaluated uncertainty of 2.5×10^{-18}, the clock has participated in the first inter-species frequency ratio measurement [3] to fulfill the $< 5 \times 10^{-18}$ requirement stated by the CCTF roadmap toward the redefinition of the second [4].

The instability in multi-clock-ion operation was initially limited by infavorable scaling of dead time due to a state preparation scheme based on spontaneous decay [5]. We have therefore implemented a repumping step using the $^3\mathrm{P}_0$ to $^1\mathrm{P}_1$ M1 transition at 482 nm, which reduces the effective $^3\mathrm{P}_0$ lifetime to 3.5 ms. The instability now follows the expected $1/\sqrt{N}$ scaling with ion number N and reaches $\sigma_y = 6(2) \times 10^{-16}/\sqrt{t}$ in operation with 4 In^+ ions.

[1] N. Herschbach *et al.*, Appl. Phys. B **107**, 891 (2012)

[2] J. Keller *et al.*, Phys. Rev. A **99**, 013405 (2019)

[3] H. N. Hausser *et al.*, arxiv:2402:16807 (2024)

[4] N. Dimarcq *et al.*, Metrologia **61**, 012001 (2024)

[5] J. Keller *et al.*, to appear in J. Phys. Conf. Ser. (2024)

Snapshotting Quantum Dynamics at Multiple Time Points

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Measurement-induced state disturbance is a major challenge in obtaining quantum statistics at multiple time points. We propose a method to extract dynamic information from a quantum system at intermediate time points, namely snapshotting quantum dynamics. To this end, we apply classical post-processing after performing the ancilla-assisted measurements to cancel out the impact of the measurements at each time point. Based on this, we reconstruct a multi-time quasi-probability distribution (QPD) that correctly recovers the probability distributions at the respective time points. Our approach can also be applied to simultaneously extract exponentially many correlation functions with various time-orderings. We provide a proof-of-principle experimental demonstration of the proposed protocol using a dual-species trapped-ion system by employing $^{171}\text{Yb}^+$ and $^{138}\text{Ba}^+$ ions as the system and the ancilla, respectively. Multi-time measurements are performed by repeated initialization and detection of the ancilla state without directly measuring the system state. The two- and three-time QPDs and correlation functions are reconstructed reliably from the experiment, negativity and complex values in the QPDs clearly indicate a contribution of the quantum coherence throughout dynamics.[1].

[1] Wang P, Kwon H, Luan C Y, et al. arXiv preprint arXiv:2207.06106, 2022.

Quantum communication protocols over a 14-km urban telecom fiber link

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We report on the implementation, characterization, and operation of quantum communication over a 14-km urban telecom fiber link. Using a single $^{40}\mathrm{Ca}^{+}$ trapped-ion quantum memory, an ion-resonant SCPD photon pair source, quantum frequency conversion, and active polarization correction of the fiber, we demonstrate high-fidelity entanglement distribution, as well as quantum teleportation from the memory to a remote telecom photon [1]. We also implement a protocol [2] for quantum key distribution based on atom-photon-entanglement. Towards the realization of a quantum repeater segment, we employ two $^{40}\mathrm{Ca}^{+}$ trapped-ion quantum memories in the same trap; asynchronously generated ion-photon entanglement is swapped to distant photon-photon entanglement by a Mølmer–Sørensen quantum gate and projective measurement on the two ions [3]. We evaluate the conditions for obtaining a repeater advantage. We also investigate the indistinguishability of two single photons generated from the two quantum memories by nanosecond laser pulse excitation. Future progress will employ an integrated ion-trap and optical-resonator assembly.

[1] S. Kucera *et al.*, arXiv:2404.04958

[2] R. Schwonnek *et al.*, Nat. Commun. **12**, 2880 (2021)

[3] M. Bergerhoff *et al.*, arXiv:2312.14805

Quantum state tracking and control of a single molecular ion in a thermal environment

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In recent years, quantum-logic spectroscopy of single molecular ions (QLS-SMI) emerged as a novel platform for high-resolution spectroscopy, offering advantages including precise initial state preparation [1], minimal line broadening from collisional or motional effects, and long interrogation times [1,2,3]. The efficient control of the quantum state of a single molecule, however, remains difficult due to environmental perturbations, notably from thermal radiation (TR) emitted by surrounding surfaces. To mitigate this effect, we developed a QLS-based protocol to track and control the evolution of molecular state [4]. By monitoring and reversing TR-induced quantum jumps from a rotational state with quantum number $J = 1$ to those with $J = 0$ and 2, we can confine the population in $J = 1$ to, on average, ~ 20 times its natural lifetime of $1.7\,s$, resulting in an improvement of our experimental duty cycle from 7% to 64%. Leveraging this improvement in state control, we performed vibrational overtone spectroscopy on CaH^+ at the 10^{-13} fractional uncertainty level. Using a single frequency comb source, we locate and probe two rotational lines within the $v = 0 \to 5$ vibrational series. We discuss the generalizability of these state control and spectroscopy techniques to other molecular species which are of astrophysical interest or suitable for various precision measurement tasks.

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

[2] Chou *et al.*, Science 367, 6485 (2020)

[3] Collopy *et al.*, PRL 130, 223201 (2023)

[4] Liu *et al.*, arXiv, 2312.17104 (2023) (accepted in Science)

Scalable, high-fidelity, all-electronic quantum computing with trapped ions at Oxford Ionics

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Broadly speaking, two types of challenges stand in the way of building useful quantum computers (QCs). First, there is a challenge of fidelity, where a useful QC must perform all the primitive operations – such as state preparation, measurement, single- and two-qubit gates – with very low errors. Second, there is a challenge of scale, where the QC architecture must allow for adding qubits without compromising performance.

At Oxford Ionics, we are building trapped-ion QCs that utilize all-electronic coherent control to address both challenges simultaneously. In this talk, I will present our architecture for scalable, chip-scale QCs. Our approach uses a shared current-carrying trace – which generates oscillating magnetic field gradients across the chip – in combination with local DC electrodes – which generate qubit-selective quasi-static electric fields – to perform parallel, site-selective coherent control. I will discuss our recent experiments which follow the all-electronic control paradigm to demonstrate record-level operation quality, achieving 99.99916(7)% single-qubit gate fidelity and 99.97(1)% Bell-state fidelity [1] in a multi-zone ion trap chip. I will also give an overview of our scheme for using chip-integrated switching networks to avoid the QC wiring bottlenecks [2]. Finally, I will discuss the broader challenges of building QCs with 1000+ qubits, and how we're approaching them at Oxford Ionics.

[1] C. M. Löschnauer *et al.*, arXiv:2407.07694 [quant-ph] (2024)

[2] M. Malinowski *et al.*, PRX Quantum 4, 040313 (2023)

Integrated Technologies for Compact and Scalable Trapped-Ion Systems

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Integrated technologies offer a pathway to provide enhanced functionali
for trapped ions by incorporating control elements—such as light deliver
detection, and electronics—into the substrate of a microfabricated surfac
electrode ion trap. Harnessing the full power of integrated photonics requir
the development of low-loss, high-performance components across a wi
range of visible wavelengths. In this talk I will discuss the MIT Lincoln La
oratory photonics platform and our recent efforts to expand the wavelengt
range of our toolkit, as well as design and implementation of components f
new photonics applications including sub-Doppler cooling and remote enta
glement generation for networking of modules in a quantum computer.

Scaling of Ion Trap Quantum Computers and Simulators

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Trapped atomic ions are the gold standard for quantum bits, with coherence and control that is not matched in any other physical platform. Trapped ion quantum computer systems are well into their engineering phase, evidenced by the fact that industrial efforts are now leading the way by approaching 99.99% two-qubit gate fidelities [1, 2, 3]. At these fidelities, there is finally a pressing need to operate with 100+ qubits in order to enter a regime of quantum advantage, without error correction. (While other qubit platforms are now turning to blind error correction with its enormous overhead, the remaining errors in trapped ion qubits are largely control errors, whose structure allows error *mitigation* to be an attractive way forward.) There is current great progress in the control of large crystals of hundreds of ions in radiofrequency [4, 5] and Penning traps [6, 7]. While there is continued work in the QCCD model of shuttling ions between trap zones [8, 2], there is renewed interest and progress in modular photonic interconnections between ion trap modules [9, 10]. Notably, this is only quantum architecture that features full-connectivity and no slowdown *at scale*. On the applications side, there has been a flurry of results with standard and benchmark algorithms, and quantum simulations of magnetic spin system in Chemistry, QCD, and other fields, with up to a few dozen trapped ion qubits. Finally, a new approach to trapped ion quantum computing and simulation exploits the internal phonon modes of crystals, adding significantly to the available Hilbert space [11].

[1] www.oxionics.com; C. M. Löschnauer *et al.*, arXiv:2407.07694 (2024).

[2] www.quantinuum.com (2024).

[3] www.ionq.com (2024).

[4] S.-A. Guo *et al.*, Nature **630**, 613 (2024).

[5] D. Kiesenhofer *et al.*, Phys. Rev. X Quantum **4**, 020317 (2023).

[6] J. Bohnet *et al.*, Science **352**, 1297 (2016).

[7] B. McMahon *et al.*, arXiv:2404.02105 (2024).

[8] D. Kielpinski *et al.*, Nature **417**, 709 (2002).

[9] J. O'Reilly *et al.*, arXiv:2404.16167, to appear in Phys. Rev. Lett. (2024).

[10] S. Saha *et al.*, arXiv:2406.01761 (2024).

[11] K. Sun *et al.*, arXiv:2405.14624 (2024).

A full-stack trapped-ion processor at the limits of classical simulation

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One of the main challenges facing large-scale quantum computing is scaling systems to more qubits while maintaining high fidelity operations. In this talk, I will describe our continued efforts at Quantinuum in scaling trapped-ion quantum computers based on the quantum charge-coupled device architecture [1]. We recently upgraded our second-generation quantum processor [2] to accommodate 56 qubits, while maintaining all-to-all connectivity and improving two-qubit gate fidelities. First, I will present benchmarking results on the 56-qubit device. Then I will present data from random circuit sampling in highly connected geometries, which was taken at unprecedented fidelities and at a scale that appears to be beyond the capabilities of state-of-the-art classical algorithms [3]. The considerable difficulty of classically simulating H2 is likely limited only by qubit number, demonstrating the promise and scalability of the QCCD architecture as continued progress is made towards building larger machines.

[1] D. J. Wineland *et al.*, Journal of Research of the National Institute of Standards and Technology **103**, 259 (1998).

[2] S. A. Moses *et al.*, PRX, **13**, 041052 (2023).

[3] M. DeCross *et al.*, arXiv 2406.02501 (2024).

Levitated nanoparticles in a linear Paul trap: a route to the quantum regime

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Almost three decades ago, nonclassical states of mechanical motion were realized with an ion in a linear Paul trap, taking advantage of the coupling between the ions' electronic and motional degrees of freedom [1]. Here, we aim to realize such nonclassical motional states with much larger objects, consisting of perhaps a billion atoms. We are in particular interested in macroscopic states, in the sense of a superposition state for which the distance between the superposed states is at least as large as the object itself. Such states would allow us both to investigate fundamental questions about quantum mechanics and to build novel sensors and transducers.

I will present experimental results with silica nanoparticles in linear Paul traps, under high and ultra-high vacuum. A common theme is to adapt techniques originally developed for trapped atomic ions, including detection via self-interference and sympathetic cooling, for the domain of nanoparticles. Quality factors above 10^{10} provide evidence of the particles' extreme isolation from their environment [2]. Recently, we have trapped a calcium ion and a nanoparticle together using a dual-frequency trapping scheme [3]. I will discuss how atomic ions may allow us in the future to prepare the nanoparticle's motion in nonclassical states and will highlight key experimental challenges.

[1] D. M. Meekhof, C. Monroe, B. E. King, W. M. Itano, D. J. Wineland, Phys. Rev. Lett. **76**, 1796 (1996)

[2] L. Dania, D. S. Bykov, F. Goschin, M. Teller, A. Kassid, T. E. Northup, Phys. Rev. Lett. **132**, 133602 (2024)

[3] D. S. Bykov, L. Dania, F. Goschin, T. E. Northup, arXiv:2403.02034 (2024)

A General Method for High Resolution Single Molecule Spectroscopy

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Single molecular ions present a highly attractive platform for high resolution and highly sensitive spectroscopy. These molecules can be held for many hours in a pristine environment, and can be motionally laser cooled into the millikelvin regime and below. Prior to this work, methods to spectroscopically study “generic” single molecules have not been demonstrated. Here, we demonstrate a novel single molecule action-spectroscopy technique that is compatible with high precision measurement, and present the first spectra ever recorded of single polyatomic gas-phase molecules, including high resolution, rotationally resolved spectra. The method is generally applicable to a wide range of polyatomic molecular ions, and promises spectral resolution comparable to state of the art quantum logic methods, with significantly less stringent experimental overhead. Progress towards extending this technique to include chiral recognition of single molecules will be discussed.

The St. Benedict facility: Precision measurements of nuclear beta decays

Sam Porter

University of Notre Dame

Precise measurements of nuclear beta decays provide a unique insight into the Standard Model due to their connection to electroweak interactions. These decays can provide constraints on the unitarity or non-unitarity of the Cabbibo-Kobayashi-Maskawa (CKM) quark mixing matrix, where non-unitarity would signal potential physics Beyond the Standard Model. The most precise of these tests involves the matrix element Vud as determined from superallowed pure Fermi beta decays, and indicates a deviation from unitarity on the order of $\sim 2.4\sigma$. As such, cross-checks from additional methods, including superallowed mixed mirror beta decays, are necessary. Vud precision from mirror decays is currently limited by the absence of precise Fermi-to-Gamow Teller mixing ratios, which are most sensitively determined via the angular correlation of the neutrino and beta particle emitted during the decay. At the Nuclear Science Laboratory (NSL) at the University of Notre Dame, the Superallowed Transition Beta-Neutrino Decay Ion Coincidence Trap (St. Benedict) is being constructed to determine the beta-neutrino angular correlation parameter of various mirror decays. We plan on measuring this correlation parameter for the beta decays of nuclei ranging from ^{11}C to ^{41}Sc using radioactive ion beams from the NSL's TwinSol separator, which will result in significantly improved precision of the Vud element of the CKM matrix from superallowed mirror transitions. The St. Benedict facility, its developmental status and first commissioning experiments will be presented.

An Integrated Laser Running an Optical Atomic Clock

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Optical atomic clocks have demonstrated revolutionary advances in precision timekeeping, but their applicability to the real world is critically dependent on whether such clocks can operate outside the laboratory. Photonic integration offers one compelling solution to address the miniaturization and ruggedization needed to enable clock portability, but brings with it a new set of challenges in recreating the functionality of an optical clock using chip-scale building blocks. The clock laser used for atom interrogation is one particular point of uncertainty, as the performance of the meticulously-engineered bulk-cavity stabilized lasers would be exceptionally difficult to transfer to chip. Here we demonstrate that an integrated ultrahigh quality factor spiral cavity, when interfaced with a 1348 nm seed laser, is able to reach a fractional frequency instability of 7.5×10^{-14} on chip. Upon frequency doubling the light to 674 nm, we use this laser to interrogate the narrow-linewidth transition of $^{88}\mathrm{Sr}^{+}$ and showcase the operation of a Sr-ion clock with short-term instability averaging down as $3.9\times10^{-14}/\sqrt{\tau}$, where τ is the averaging time. Our demonstration of a high-performance optical atomic clock interrogated by an integrated spiral cavity laser opens the door for future advanced clock systems to be entirely constructed using lightweight, portable, and mass-manufacturable integrated optics and electronics.

Harnessing spin-phonon entanglement in two-dimensional ions crystals for quantum information tasks

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Two-dimensional crystals of ions generated by the use of a Penning trap offer the possibility of scalable quantum information processing with samples of as many as 500 ions. Up to date, nevertheless, most of the protocols used in the Penning trap typically operate in a far-detuned regime where the phonons are used only to mediate interactions between the spins. Consequently, the generated spin–spin interactions are slow compared to the original atom-phonon coupling, making any generated entanglement susceptible to decoherence. In this talk I will discuss schemes that resonantly couples internal and motional degrees of freedom and fully leverages the available spin-phonon coupling. This is achieved by implementing various spin-boson models that can be concatenated together to prepare a desired final quantum state. In particular we describe simple protocols to create metrologically useful states for electric field sensing [1], phase estimation [2, 3] and entangled states for quantum teleportation [4] which enjoy the beneficial short timescales associated with the resonant interactions. Furthermore, we characterize the fundamentally achievable sensitivity or fidelity of the protocols as a function of particle number. This work suggests new opportunities for the preparation of many-body states with tailored correlations for quantum-enhanced metrology and information processing in spin-boson systems.

[1] K. Gilmore*et al.*, Science **373**, 673 (2021)

[2] D. Barberena *et al.*, Quantum Sci. Technol. **9**, 025013 (2024)

[3] R. J. Lewis-Swan *et al.*, Phys. Rev. Lett. **132**, 163601 (2024)

[4] M. M. Khan *et al.*, arXiv:2405.19536v1 (2024)

Metastable and Ground State Qubits in Compact Penning Traps

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Trapped atomic ions are useful platforms for experimental quantum sensing, simulation, and computation. Previous work has demonstrated the utility of Penning ion traps for controlling large (> 100-ion) Coulomb crystals for quantum-enhanced metrology [1] and quantum simulation of Ising spin models [2] using ground-state qubits in a large trap magnetic field (> 4 T). At GTRI, we have developed compact Penning traps built with room-temperature permanent-magnet arrays replacing the more traditional cryogenic superconducting coils. Our compact Penning traps enable precise control of high-magnetic-field (~ 1 T) optical, metastable, or ground state qubits in a form factor similar to that of traditional Paul traps. Notably, the large Zeeman shifts in the Penning trap permit novel realizations of *omg* qubits [3] in species without hyperfine structure (e.g. $^{40}\mathrm{Ca}^+$). We describe a recent demonstration of individual optical addressing of metastable $^{40}\mathrm{Ca}^+$ qubits within rotating triangular arrays using a tightly-focused infrared laser beam [4], and progress towards sub-Doppler laser cooling and two-qubit entangling gates in the same apparatus.

In a separate compact system, we have integrated a Fabry-Perot optical enhancement cavity with a Penning trap. We describe progress towards collective, cavity-enabled quantum non-demolition measurements of $^{40}\mathrm{Ca}^+$ arrays for robust preparation of Greenberger-Horne-Zeilinger (GHZ) spin states, motivated by the recent proposal of Alexander *et al.* [5].

[1] J. G. Bohnet *et al.*, Science 1297, **352** (2016)

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

[3] D. T. C. Allcock *et al.*, Appl. Phys. Lett. 214002, **119** (2021)

[4] B. J. McMahon *et al.*, arXiv:2404.02105 (2024)

[5] B. Alexander, J. J. Bollinger, and H. Uys, Phys. Rev. A 062303, **101** (2020)

Toward quantum information processing with high-dimension systems

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Multi-level quDits have many potential applications in quantum information processing. In an era where qubit counts are still quite challenging to scale, making more efficient use of the quantum resources available in the internal structure of our ions presents an additional path to extract more utility from a given ion register. However, qudits are notably underexplored compared to the well understood trapped ion qubits, owing in large part to the challenges of taming the experimental complexity of manipulating many atomic transitions.

This talk focuses on Ba^+ ions, which have a multitude of spectrally resolved stable and metastable sublevels (decay times >30 seconds), and hence are a promising candidate to host high performance qudits. I will present my group's recent results on mapping and manipulating the dozens of electric quadrupole transitions in $^{137}Ba^+$. We employ rapid calibration techniques, in which the interrogation times are independent of qudit dimension, to achieve high-fidelity control of several tens of transitions within the same experimental pulse sequence. Using these tools, we implement state preparation and readout of qudits with up to 25 states, achieving fidelities over 99.5%. We additionally present preliminary results on coherent control of qudits with as many as 9 states. As an outlook, I will discuss prospects for integrating qudit manipulations into the multi-ion quantum processors under development at Waterloo.

Towards High-Rate Quantum Repeaters Using a Trap-Integrated Fiber-Based Optical Cavity

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Quantum networking aims to generate distributed entanglement as a resource for applications such as distributed quantum computation, secure communication, and quantum sensing. Trapped ions offer many advantages as nodes in a quantum network, including long coherence times and high-fidelity local gate operations. However, thus far remote entanglement rates have primarily been limited by low photon collection efficiency.

In this talk I will present the NIST Ion Storage Group's progress towards developing a long-range, high-entanglement-rate quantum repeater. Our strategy involves using a fiber-based optical cavity, integrated with a surface electrode trap at cryogenic temperatures, to achieve high photon collection efficiency while maintaining high mechanical stability and low ion motional heating. The emitted photons can be efficiently and coherently converted to telecom wavelengths, facilitating long-distance networking. I will in particular discuss our recent results measuring the behavior of an ion positioned hundreds of microns from a bare, cryogenic optical fiber, and our progress towards creating high-finesse, fiber-based optical cavities using microfabricated mirrors.

Device research for scaling to the next order-of-magnitude TIQC

Daniel Stick[1], M. Delaney[1], M. Eichenfield[1,2], M. Gehl[1], C. Hogle[1], J. Kwon[1], B.K. McFarland[1], H.J. McGuinness[1], J.D. Sterk[1]

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Current trapped-ion quantum computers (TIQC) store and independently control tens of ions. Supporting an order-of-magnitude expansion to TIQCs with hundreds of ions will require using multiple in-development and new technologies. In this presentation I will discuss the ones Sandia is working on, including reduced capacitance techniques [1], passive electrical components, integrated waveguides and diffractive gratings [2], and optical modulators [3].

[1] J.D. Sterk *et al.*, “Multi-junction surface ion trap for quantum computing”, arXiv:2403.00208v1 (2024)

[2] J. Kwon *et al.*, “Multi-site integrated optical addressing of trapped ions”, Nature Communications 15, 3709 (2024)

[3] C.W. Hogle *et al.*, “High-fidelity trapped-ion qubit operations with scalable photonic modulators”, npj Quantum Information 9, 74 (2023)

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Quantum-Limited Detection and Special Relativity: Improving the Electron Magnetic Moment Measurement by a factor of 10

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The most precise test of the Standard Model is the comparison of the measured [1] and predicted values of the electron's magnetic moment [2]. The measurement is performed through detecting the image charge of a single electron using a sensitive detector. We aim to couple the electron to a quantum-limited detector (SQUID), reducing its temperature by a factor of 20. In this new detection scheme, we aim to non-destructively readout the relativistic mass shift due to changes in the particle's cyclotron and spin states. The SQUID amplifier and its enabling technologies– a low fringe field superconducting solenoid and superconducting shield, will be discussed. These new techniques should enable a tenfold improvement in measurement precision and will test the Standard Model at unprecedented precision.

**supported by NSF, SQMS DOE center, and the Templeton Foundation*

[1] X. Fan *et al.*, Phys. Rev. Lett. **130**, 071801 (2023)
[2] R. H. Parker *et al.*, Science **360** 6385 (2018); L. Morel *et al.*, Nature **588** 7836 (2020); T. Aoyama *et al.*, Atoms **7.1** (2019)

Locally manipulating trapped ions with integrated wires

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We discuss dressing trapped ions with the near field of a trap integrated wire. Ramping a dressing field on/off adiabatically before/after an operation changes its effective Hamiltonian. The amplitude and detuning of the dressing field act as tunable degrees of freedom we can use to 'customize' the properties of any operation. We propose three use cases for this general tool. First, we can generate 'artificial' clock states, where we eliminate the (assumed to be small) linear sensitivity of a qubit. Second, we can break the degeneracies that often complicate shelving at low quantization fields—allowing us to implement operations with linearly polarized microwaves that would, otherwise, require circular polarization. Finally, we can implement laser-free single qubit gates on a set of 'target' ions using fields that are separated from the rest of the computer in frequency space [1, 2].

[1] R. T. Sutherland, S. D. Erickson, Phys. Rev. A **109,** 022620 (2024)

[2] R. T. Sutherland, arXiv:2407.09623

Experimental preparation and control of logical qubits for bosonic-error correction

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I will discuss recent experimental efforts in preparing and manipulating logical states in the bosonic modes of a single trapped ion. First, numerically optimized pulses are used to deterministically prepare arbitrary bosonic states, notably Gottesman-Kitaev-Preskill (GKP) and binomial states, which have important properties for bosonic error-correction [1]. Second, I report ongoing efforts to demonstrate a universal gate set for GKP logical qubits, comprising single-qubit gates and a two-qubit controlled-Z entangling gate. The gates are both deterministic and preserve the finite-energy envelope of the physical GKP states. We also created a GKP logical Bell state in a single step from vacuum. Third, I present recent results on using bosonic states for quantum-enhanced multi-parameter sensing.

[1] V. G. Matsos *et al.*, arXiv:2310.15546, (2023)

Laser-free Quantum Logic Spectroscopy of Trapped Molecular Ions

H. Wu[1,2,3], G. Mitts[1,2,3], C. Ho[1,2,3], J. Rabinowitz[1,2,3] and E. R. Hudson[1,2,3]
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[3] Center for Quantum Science and Engineering, University of California Los Angeles, Los Angeles, CA, USA

Dipolar molecular ions offer a rich variety of states, ranging from Λ-doublet parity states to rotational states, making them ideal platforms for encoding information and performing quantum operations using microwave fields. It has been proposed that by applying a spatially varying microwave electric field, these states can be utilized to implement electric-field gradient gates (EGGs) [1].

In the first part of my talk, I will discuss the engineering of electric-field gradient gates (EGGs) with a molecular ion through the application of a quadrupole microwave electric field. I will then explore the adaptation of EGGs for use with $H^{35}Cl^+$ molecular ions to enable state preparation and measurement (SPAM).

The second part of my talk will focus on the development of a single atomic ion as a quantum vector signal analyzer (QVSA) [2] for *in-situ* calibration of the electric field's strength and distribution relevant to EGGs. Additionally, I will demonstrate how the QVSA can be employed for wideband quantum sensing of the frequency, phase, and amplitude of electric fields. We have successfully extended the tunable frequency range by over three orders of magnitude compared to previous measurements in trapped ions.

Finally, in the last part of my talk, I will address the implementation of dynamically decoupled electric-field gradient gates, which hold potential to accelerate the search process in molecular spectroscopy by more than one order.

[1] E. R. Hudson and W. C. Campbell, Phys. Rev. A **104**, 042605 (2021).

[2] H. Wu *et al.*, arXiv:2311.12263 [quant-ph].

Laser spectroscopy of triply charged ^{229}Th isomer for a nuclear clock

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Thorium-229 (^{229}Th) has an excited nuclear state (isomer, $^{229\mathrm{m}}$Th) at only 8.4 eV from the nuclear ground state, which enables direct laser spectroscopy of the ^{229}Th nucleus. A nuclear clock based on the transition frequency between the nuclear ground state and isomer is expected to achieve high accuracy due to its small sensitivity to fluctuations of external electromagnetic fields [1, 2]. Successful laser excitation of ^{229}Th nuclei embedded in crystals has been reported recently [3, 4].

We aim to realize highly accurate nuclear clocks based on isolated ^{229}Th ions in a trap. To this end, a triply charged ^{229}Th ion (^{229}Th^{3+}) is suitable due to the availability of closed electronic transitions enabling laser cooling, laser-induced fluorescence detection, and state preparation of ions [5]. However, essential parameters of $^{229\mathrm{m}}$Th^{3+} for a nuclear clock, such as its nuclear decay lifetime, were unknown. We trapped $^{229\mathrm{m}}$Th^{3+} obtained as recoil ions from a uranium-233 source, where the isomer ions were produced with a branching ratio of about 2% (the remaining 98% of the nuclei were in the ground state). We developed a laser spectroscopy technique to extract signals from isomer ions and determined nuclear decay lifetime of $^{229\mathrm{m}}$Th^{3+} [6]. Furthermore, by measuring the hyperfine constants of $^{229\mathrm{m}}$Th^{3+}, we determined various nuclear properties of $^{229\mathrm{m}}$Th. We also developed a technique to enrich isomer ions up to more than 90% in a trap for future research on $^{229\mathrm{m}}$Th^{3+}, such as precise determination of the sensitivity of nuclear clocks to variations in the fine structure constant and investigation of unique nuclear decay via an electron bridge.

[1] E. Peik and Chr. Tamm, Europhys. Lett. **61**, 181 (2003).

[2] C. J. Campbell *et al.*, Phys. Rev. Lett. **108**, 120802 (2012).

[3] J. Tiedau *et al.*, Phys. Rev. Lett. **132**, 182501 (2024).

[4] R. Elwell *et al.*, Phys. Rev. Lett. **133**, 013201 (2024).

[5] C. J. Campbell *et al.*, Phys. Rev. Lett. **106**, 223001 (2011).

[6] A. Yamaguchi *et al.*, Nature **629**, 62 (2024).

3D Monolithic Trap for Quantum Simulation and Computation

Roman Zhuravel[1], April Sheffield[1], Michael Straus[2], Abhishek Menon[1], Devon Valdez[2], Midhuna Duraisamy Suganthi[1,3], Uday Singla[2], Visal So[1], Xinyi Dai[2], George Tomaras[1,3], Yuanheng Xie[2], Norbert M Linke[2], and Guido Pagano[1,3]

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Quadrupole-based traps are versatile tools for AMO research and specifically for the ion-trapping community widely used in quantum computing, simulation, networks and sensing. Despite the advances of planar chip microfabricated traps, 3D blade traps still offer the advantages of ease of use, eV-deep trapping potentials, robustness to stray fields, larger ion-electrode distance (low heating rates), and wider and multi-directional optical access. A monolithic segmented blade trap represents further advancement in the blade trap design as it offers better structural accuracy by eliminating the need for manual alignment, a compact structure, a potentially more elaborate design, as well as better maneuverability and repeatability.

Here we present the design of a compact, highly versatile monolithic blade trap manufactured by Translume Inc. With a new optimized design to reduce the capacitance, we demonstrate that we can drive the trap at ¿30 MHz at 1.6 kV pkpk without breakdown or damage. We characterize the thermal properties of the trap, the trapping potential uniformity, and the residual micromotion. Testing of the complete system, including the vacuum surrounding and the optical system, was independently performed on two separate assemblies at both Rice and Duke University. Our measurements show promising performance and support further development and implementations of this novel design, making ion-trapping easier and more affordable.

Finally, I will present our recent results [1] on the simulation of molecular electron transfer with a multi-species trapped-ion crystal. This setting enables precise and independent control of all model parameters, namely the donor-acceptor gap, the electronic and the spin-phonon coupling, as well as the coupling to the bath.

[1] So, Visal, et al. ”Trapped-Ion Quantum Simulation of Electron Transfer Models with Tunable Dissipation.” arXiv preprint arXiv:2405.10368 (2024).

2 Poster Abstracts - Session 1 - Tuesday Aug 13th, 4pm

Quantum Networking with Trapped ^{88}Sr^{+} and ^{43}Ca^{+} Ions

E. M. Ainley, D. Main, A. Agrawal, P. Drmota, D. P. Nadlinger, B. C. Nichol, C. J. Ballance, P. Juhasz, R. Srinivas, G. Araneda, D. M. Lucas
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By interfering photons from two network nodes separated by 2 m, we create remote entanglement between two ^{88}Sr^{+} ions with 96 % fidelity at a rate of $\sim$100 s^{-1}. This remote entanglement enabled demonstrations of device-independent QKD [1], and a network of entangled optical atomic clocks [2]. Additionally, the integration of robust quantum memory qubits in ^{43}Ca^{+} [3] was central to our demonstration of deterministic and verifiable blind quantum computing [4], and has recently enabled the storage of remote entanglement for up to 10 s. Finally, we present progress towards remote entanglement between nodes separated by 200 m.

[1] D. P. Nadlinger *et al.*, Nature **607**, 682-686 (2022)

[2] B. C. Nichol *et al.*, Nature **609**, 689-694 (2022)

[3] P. Drmota *et al.*, Phys. Rev. Lett. **130**, 090803 (2023)

[4] P. Drmota *et al.*, Phys. Rev. Lett. **132**, 150604 (2024)

Penning-trap eigenfrequency measurement via a laser-cooled ion

J. Berrocal[1], D. Yousaf[1], J. Sánchez[1], F. Domínguez[1], A. Carrasco-Sanz[2], and D. Rodríguez[1]
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A new method for the determination of the eigenfrequencies of a laser-cooled ion in a Penning trap [1] based on the detection of optical photons has been demonstrated [2]. It relies on the measurement of the ion's motional amplitude while the system is Doppler-cooled after the excitation at one of its eigenfrequencies. It has recently been extended to two-ion Coulomb crystals of calcium isotopes, probing the six eigenmodes in the Doppler limit. After being upgraded with a new cryogen-free magnet, the Penning-trap setup is under commissioning to reach the quantum regime [3].

[1] D. Rodríguez, Appl. Phys. B **107**, 1031 (2012)

[2] J. Berrocal *et al.*, Phys. Rev. Research **6**, L012001 (2024)

[3] J. Cerrillo and D. Rodríguez, EPL-Perspective **134**, 38001 (2021)

Neutral Atoms in Optical Tweezers as Flying Qubits for Scaling up Trapped Ion Quantum Computer

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We propose to combine the neutral atom and the trapped ion qubits in one scalable modular architecture that uses shuttling of the neutral atoms in optical tweezers to realize quantum interconnects between the trapped ion qubit registers. These interconnects are *deterministic*, and thus may be performed *on-demand*. The proposed protocol is as follows: A tweezer-trapped atom is brought near a trapped ion in a small (30-ion) chain, and a collisional entangling gate is performed. Then the neutral atom is transported to another trapped ion chain in the modular ion trap and entangled with another ion, thus entangling the two separate ion chains. With realistic dipole trap parameters, the neutral atom can be moved over a 1 mm distance in tens of μs, and the collisional gates may be performed in tens of μs as well, thus enabling a remote entanglement generation rate of several kHz, which is more than an order of magnitude higher than the current state-of-the-art for the photonic interconnects.

Integrated photonics for photon mediated entanglement generation and sub-Doppler cooling

Ethan R. Clements[1], Felix Knollmann[1], Sabrina Corsetti[1], Zhao-Yi Li[1], Aaron Leu[3], Ashton Hattori[1], Milica Notaros[1], Tal Sneh[1], Reuel Swint[2], Patrick T. Callahan[2], Dave Kharas[2], Gavin N. West[1], Thomas Mahony[2], Colin D. Bruzewicz[2], May E. Kim[2], Cheryl Sorace-Agaskar[2], Robert McConnell[2], Jelena Notaros[1], Isaac L. Chuang[1], and John Chiaverini[2]
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Trapped-ion platforms are being developed for a range of quantum applications, all these require or will benefit from entanglement between particles. Additionally, many applications require ions to be cooled to their motional ground state, a procedure that often has a large time overhead. Here we present tests of a trap-integrated collection grating which is used to collect ion fluorescence, and could enable integrated photon mediated entanglement. Further, we present tests of emission grating pairs which generate optical polarization gradients used for sub-Doppler cooling.

Towards an Optical Frequency Standard for the NIST Timescale

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To correct frequency drifts and random-walk of phase in hydrogen masers and cesium beam clocks that form the timescale at NIST, it is desirable to have an optical frequency standard with high operational uptime and inaccuracy $< 1\times10^{-16}$. We present progress on the development of an optical clock based on the $S_{1/2} \rightarrow D_{5/2}$ transition of the $^{88}\mathrm{Sr}^+$ ion at NIST. Trapping is achieved with a novel manufacturable spherical radio frequency (RF) trap design [1] using a single photonic crystal fiber to deliver the necessary wavelengths (all between 400 nm and 1100 nm) to the ion. Operation at the “magic” trap RF drive frequency [2] should enable low systematic uncertainty related to micromotion without complex experimental overhead.

[1] D. R. Leibrandt *et al.*, US Patent 11651949B2 (2023)

[2] A. A. Madej, *et al.*, Phys. Rev. Lett. **109** 203002 (2012)

Low-Crosstalk, Silicon-Fabricated Optical Waveguides for Laser Delivery to Matter Qubits

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Reliable control of quantum information in matter-based qubits requires precisely applied external fields, and unaccounted for spatial cross-talk of these fields between adjacent qubits leads to loss of fidelity. We report a CMOS foundry-produced, micro-fabricated silicon nitride optical waveguide for addressing a chain of eight, unequally-spaced trapped barium ions with crosstalk compatible with scalable quantum information processing. The crosstalk mitigation techniques incorporated into the chip design result in a reduction of the measured optical field by at least 50.8(1.3) dB between adjacent waveguide outputs near 650 nm and similar behavior for devices designed for 493 nm and 585 nm [1].

[1] Craft, Clayton L., et al. ”Low-Crosstalk, Silicon-Fabricated Optical Waveguides for Laser Delivery to Matter Qubits.” arXiv preprint arXiv:2406.17607 (2024).

Toward quantum logic spectroscopy on radium-based molecular ion

H. Dan[1], H. Li[1], M. Fan[1], R. A. Ready[1], S. Kofford[1], R. Kwapisz[1], A. Sawhney[1], M. Brzeczek[1], A. M. Jayich[1]

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Spectroscopy with radium-based molecular ion offers enhanced sensitivity for probing fundamental physics. We have trapped and laser cooled ^{224}Ra^{+} [1] and ^{225}Ra^{+} [2] ions as a first step towards spectroscopy of radium-bearing molecules. We performed multiple spectroscopy measurements on properties of the low-lying states of radium ions, including a refined measurement on the $D_{5/2}$ state lifetime and the first measurement on the $D_{3/2}$ state lifetime. We have also synthesized radium-based molecular ions in a room temperature trap, and are working toward a molecular ion experiment in a cryogenic environment.

[1] M. Fan *et al.*, Phys. Rev. Research 5, 043201 (2023)

[2] R. Roy *et al.*, arXiv:2407.14721 (2024)

Initial design of a full stack quantum control framework for trapped ion quantum information processors

Collin J. C. Epstein[1,2], Anastasiia Bershanska[1,2], Yi Hong Teoh[1,2], Benjamin MacLellan[1,2,3], Sehmimul Hoque[1], Rajibul Islam[1,2,3], Roger Melko[1,2,3], [1,2]Crystal Senko

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We present design principles for a full stack quantum control framework for trapped ion apparatuses using ARTIQ control systems. The framework expands the accessibility of trapped ion quantum information processors by allowing experiments to be expressed at multiple levels of abstraction appropriate to the user and experiment. The modular design of the framework, influenced by and expanding on DAX, simplifies control system implementation and improves transfer of experiments between apparatuses. Here, we describe trapped ion quantum computer control system framework design principles, apparatus calibration considerations, and prototype expressions for specifying quantum simulation and atomic physics experiments.

Quantum Networking with a Metastable ^{88}Sr+ Qubit

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Network-based modular architectures are a path to scale up ion-trap quantum computers and connect distant nodes. Ion-entangled photonic qubits make this connection by passing through optical fibers, which may need to span many kilometers. For medium-distance (10 km) quantum networks, the $\mathrm{P}_{1/2} \rightarrow D_{3/2}$ transition in ^{88}Sr+ has low loss in standard telecom fibers and can be used without requiring quantum frequency conversion. We report preliminary results for ion-photon entanglement and single-qubit operations in our metastable qubit.

Strategies and applications for implementing quantum error correction in molecular ion rotation

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Novel quantum information encoding schemes are possible in the rotational degrees-of-freedom in molecules which are not available in atoms.[1] The dominant errors in such systems are absorption and emission events due to thermal radiation and spontaneous decay, dephasing, and collisions. We have developed an implementation strategy for sequential and dissipative quantum error correction for absorption-emission errors.[2] I also discuss experimental progress toward state preparation, coherent control, and creation of rotational superpositions in CaOH^{+} ions in a linear Paul trap. This could pave the way for exploring the applications of trapped molecular ions in quantum computing and fundamental physics.

[1] S. Jain *et al.*, arXiv:2311.12324 [quant-ph] (2023)

[2] B.J. Furey *et al.*, arXiv:2405.02236 [quant-ph] (2024)

Towards direct telecom wavelength ion-photon entanglement with trapped Yb$^+$

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Trapped ions are an interesting platform for quantum networking because ion-qubit coherence is long, high-fidelity quantum logic gates are routine and high-fidelity ion-photon entanglement has been demonstrated in several labs. For fiber-based networks with node-node spacing in ecxess of 10 km, it is imperative to use telecom-fiber compatible wavelengths. Our lab is exploring generation of ion-entangled photons at both 1345 nm and 1650 nm in Yb$^+$ without dependence on quantum frequency conversion. Aiming to exploit dipole transitions natively at these wavelengths from the $^2P_{3/2}$ manifold to the metastable $^2D_{3/2}$ and $^2D_{5/2}$ manifolds, we present work towards populating the $^2P_{3/2}$ level using a two step process mediated by the D manifolds, circumventing the need for UV lasers. This also avoids laser light at the collection wavelength or the possibility of multiple excitations, in principle guaranteeing high purity spontaneously-emitted single photons.

Stimulated Raman 2-qubit logic gates in metastable trapped-ion qubits

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The *omg* architecture [1] for trapped-ion quantum computing makes use of multiple qubit encodings to avoid crosstalk between coherent and dissipative operations. One type of qubit this scheme employs is the metastable (m) qubit, which has not been widely studied. We have implemented m qubits in the $D_{5/2}$ manifold of $^{40}Ca^+$ and performed one- and two-qubit stimulated 976 nm Raman gates with erasure-corrected fidelities greater than 99%. We perform these gates using laser beams far red detuned of the 854 nm $D_{5/2}$ to $P_{3/2}$ transition and find that the spontaneous Raman scattering error rates can be lowered such that they are no longer a limiting factor in achieving fidelities needed for fault-tolerance [2].

[1] D. T. C. Allcock *et al.*, J. Appl. Phys. Lett. 119, 214002 (2021)

[2] I. D. Moore *et al.*, Phys. Rev. A 107, 032413 (2023)

Building a Stylus Trap and Deep Parabolic Mirror to Study and Control Quantum Jumps

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In this poster we present a method for studying quantum jumps in trapped barium ions using a stylus trap and deep parabolic mirror. This novel design minimizes the solid angle blocked by the trap electrodes allowing about 95% of the photons from the ion to hit the surrounding mirror. Combined with the 90% reflectivity of the bare aluminum mirror, this experimental design results in a total single photon collection efficiency of over 85%. High quantum efficiency single photon detectors, such as avalanche photodiodes or transition-edge detectors, will be used to maximize the overall photon detection efficiency. Part of the motivation for this research comes from work of Minev et al. [1], who found they could predict, and even reverse, a quantum jump in a superconducting artificial three-level atom. Once our trap is complete, we plan on attempting to replicate these results.

[1] Minev, Z K *et al.*, To catch and reverse a quantum jump mid-flight. Nature **570**, 200–204 (2019)

Trapped Electrons in a linear Paul trap

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Recent advancements in quantum computing have introduced trapped electrons as a potential qubit system. They have the potential of exhibiting long coherence times, akin to ions, but with the added advantage of faster gate operations. Furthermore, using electron spins as qubit states, state leakages are inherently eliminated due to the simplicity of the spins' two-level system. Being a novel system, challenges persist in trapping, controlling, and readout at both room and cryogenic temperatures. Here we report on our progress including successfully trapping electrons at room temperature in a linear Paul trap and we will give an update on our cryogenic system designed to read out the quantum state of a single electron.

Wideband Vector Field Sensing via Motional Raman Transitions

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Despite unprecedented control over trapped ions and their ubiquity in precision metrology, field sensing in trapped ions has heretofore been limited to narrowband measurements about a static secular frequency.

We describe and demonstrate a novel technique [1] that allows for wideband amplitude, frequency, and phase sensing of an electric field while maintaining leading-edge sensitivities. By applying quadrupole microwave fields about a dipole field of interest, we engineer a motional Raman transition that causes a phase-sensitive displacement.

Our scheme requires only the trap electrodes and is thus available to all ion trap architectures.

[1] H. Wu *et al.*, Quantum Vector Signal Analyzer, arXiv:2311.12263 (2023)

Fast entangling gates for ion traps with mixed species

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Entangling gates for trapped ions typically resolve specific collective motional modes, gaining robustness from their adiabatic condition. 'Fast gates' allow arbitrary motional excitations, removing speed limitations at the cost of increasing laser control requirements. Fast gates also offer improved scalability for long ion chains, and can operate between nearby trap arrays.

Multi-species ion traps are potentially useful for scaling via photonic interconnects, sympathetic cooling and quantum error correction. Adiabatic gates strongly constrain choices of ions and transitions, as all ions are driven collectively. This issue does not exist for fast gate schemes, which excite individual ions with individual laser pulses. We examine fast gate design for multi-species ion traps. We find high-fidelity fast gate solutions that are robust to the mass ratios and Lamb-Dicke parameters of the ion species, providing improved performance and more flexible choices of ion species.

Machine Learning Accelerated Temporal Photon Shaping with a Trapped Ion

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In quantum networks and especially hybrid systems, efficient quantum information transfer hinges on the indistinguishably of exchanged photons. Achieving this is challenging due to the different lifetimes of qubit emitters, necessitating precisely tailored excitation pulses to ensure photons have matching excitation probabilities, temporal amplitudes, and phases. Traditional optimization methods like genetic algorithms and Bayesian optimization, although effective, can be slow and struggle with parameter drift over time. A novel machine learning approach presented here significantly reduces the optimization steps required to match photon temporal waveforms, facilitating rapid calibration essential for scaling large quantum networks utilizing photonic interconnects. Additionally, incorporating phase modulation in laser driving pulses can generate photon waveforms with temporal waveforms not limited by the lifetime, without the need of a cavity, advancing the goal of remotely entangling an $^{171}Yb^{+}$ ion with a ZnO solid-state spin donor qubit.

Individual spin-state detection of dynamic 2D ion crystals for quantum simulation in a Penning trap

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Penning traps are a promising platform for quantum simulation and sensing using 2D crystals with hundreds of ions. To enable single-shot, individual spin state readout, we developed a scalable technique utilizing a time-correlated single-photon-counting camera and a neural-network-based object detection algorithm to localize individual ion positions with high efficiency [1]. We achieved a 90% success rate for the detection of the ion positions and a 94(2)% spin-state fidelity using a time-binned maximum likelihood method. Additionally, we demonstrate creating titled optical dipole force wavefronts for tuneable spin-spin and spin-motion coupling using adjustable Raman lasers, a key step towards performing quantum simulations [2].

[1] R. Wolf *et al.*, Phys. Rev. App. 21, **054067** (2024)

[2] J. Pham *et al.*, Adv. Quantum Technol., **2400086** (2024)

High-fidelity remote entanglement of trapped ions mediated by time-bin photons

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Photonic interconnects between quantum processing nodes are likely the only way to achieve large-scale quantum computers and networks. Various degrees of freedom of photons can be used to generate entanglement between network nodes, such as polarization, time bins, frequency etc. Polarization-based encodings have been used for high rate entanglement generation between ion traps, however fidelity has been limited by polarization errors. Photonic time bin qubits are a strong candidate for networking due to their intrinsic insensitivity to polarization errors, especially when nodes are connected by long-distance fibers. We herald entanglement of two remote ions through detection of time bin photons, achieving a Bell-state fidelity of 97%. We further discuss spin-motion coupling and its effects on entanglement fidelity.

On the Integration of Miniature Optical Cavities with a Linear Ion Trap for Quantum Networking

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Optical cavity mediated photonic interconnects can solve the long-standing scalability challenge in ion trap systems[1, 2]. Yet, an efficient coupling between ions in a linear trap and an optical cavity has not been demonstrated to date. Through numerical and analytical studies, we identify that the conventional integration of optical cavities with blade-type and surface-type traps leads to significant distortion of the trapping field which renders the trap no longer capable of trapping a chain of ions in the regions of interest. We propose remedies that suppress the heating and charging effects from integrated cavities and that restore the trapping potential.

[1] H. J. Kimble The quantum internet. *Nature* **453**, 1023-1020 (2008).

[2] H. Takahashi, *et al.* Strong coupling of a single ion to an optical cavity. *Phys. Rev. Lett.*, **124**, 013602 (2020).

Progress towards a Barium-133 trapped ion quantum processor

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We present our progress towards assembly of a Ba-133 trapped ion testbed. The radioactivity of Ba-133 restricts us to microgram quantities in order to satisfy safety regulations. We outline two novel recipes for preparation of $BaCl_2$ ablation targets which optimize the production of neutral atoms and facilitate efficient ion loading [1]. We also discuss the progress and challenges in assembling our unique apparatus which offers enhanced optical access and UHV for trapping and manipulating long chains of ions. These challenges include bringing in-vacuum electrical connections to ∼100 DC electrodes on a surface trap and mitigating the rapid oxidation of a metallic barium atomic source. Finally, we describe a novel individual addressing system that provides maximum flexibility in controlling individual ion qubits.

[1] N. Greenberg *et al.*, Rev. Sci. Instrum. 95, 045117 (2024)

Quantization of normal-micromotion modes of an ion string

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The normal mode structure of an ion string is well known, and understanding it is essential for conducting entangling gates between arbitrary qubit pairs within the string. On the other hand, the effect of micromotion on an ion string is not well studied and usually neglected in the pseudopotential approximation. We theoretically derive a combined structure for the secular motion and micromotion through what we define as the normal-micromotion mode. We quantize it for direct calculations of quantum operations involving ion strings beyond the pseudopotential approximation. In particular, the behavior of the ion string subject to an external force is presented and utilized for two-dimensional micromotion compensation in an RF trap. In the regime of linear motion, the theory is shown to agree well with experimental data. Finally, the ongoing development in theory for utilizing both electrical and optical forces for quantum operations in search of novel addressing schemes are discussed.

Micro-cavity-integrated surface electrode chip for enhanced photon collection in trapped ion quantum computers

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Achieving high photon collection efficiency from a single trapped ion is essential for implementing fast remote entangling gates, a critical component in developing large-scale trapped ion quantum computers[1]. Our poster presentation describes design optimization, fabrication, and characterization methods for an integrated surface electrode chip trap with microcavity and fiber coupling optics. The integrated system comprises a surface electrode chip, concave micromirror, flexure mount, and integrated optics for fiber coupling. This comprehensive approach to integrating microcavities into surface electrode chip traps is anticipated to significantly improve photon collection efficiency.

[1] C. Monroe *et al.*, Phys. Rev. A **89** (2014)

A Novel 2D-3D Photonic Integrated Circuit for Broadband, High-Efficiency Control of Trapped Ion Qubit Arrays

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Photonic integrated circuits (PICs) play a pivotal role in scaling trapped ion quantum systems. However, current quantum PICs suffer from low ion densities. We present a novel quantum PIC for individual optical control of closely-spaced trapped ion qubits. Our device achieves effectively achromatic beam focusing from 405 nm to 810 nm (and beyond) via a planar waveguide lens and a 3D-printed biconic mirror. Moreover, we have measured 30 dB crosstalk at a 5 µm pitch for the 532 nm and 729 nm barium and calcium gate wavelengths, surpassing the state-of-the-art. Finally, our monolithic surface trap integration aims to mitigate the detrimental effects of photoinduced dielectric charging, presenting a potential leap forward in ion trap technology.

Towards a transportable optical clock based on quantum-logic spectroscopy of trapped Al^+ ions

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Optical atomic clocks demonstrate remarkable fractional systematic and statistical frequency uncertainties on the order of 10^{-18}, paving the way for novel applications. One such application is height measurements in relativistic geodesy at the centimeter level. We have set up a clock based on the $^1S_0 \rightarrow {}^3P_0$ transition in $^{27}Al^+$. A co-trapped $^{40}Ca^+$ ion allows state detection and cooling through quantum logic spectroscopy and sympathetic cooling. We present the transportable clock setup integrated inside 19" racks including the physical package, several laser systems and an optical comb. This setup also features a highly stable clock laser system at 267 nm with a fractional instability of 2×10^{-16} for average times between 0.2 s and 200 s. Furthermore, we present initial measurements with trapped and cooled $^{40}Ca^+$ ions.

Interaction graph engineering in trapped-ion quantum simulators with global drives

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Trapped-ion quantum simulators usually use globally addressed driving fields—typically laser beams addressing the whole ion chain. Here, we broaden and delimit the set of spin-spin interactions achievable using exclusively global driving fields. We find that new categories of interaction graphs become achievable with perfect or near-perfect theoretical fidelity by tailoring the coupling to each crystal mode, or by shaping the trapping potential with anharmonic terms. We also derive a rigorous test to determine whether a desired interaction graph is accessible with global fields. These tools broaden the reach of trapped-ion simulators so that they may more easily address open questions in materials science and quantum chemistry[1].

[1] A. Kyprianidis *et al.* 2024 *New J. Phys* **26** 023033

Low Vibration Closed Cycle 4K Flow Cryostat for Ion-Cavity Experiments

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Scaling to quantum processors with 1000's of ions is expected to require entanglement distribution using ion-photon interfaces mediated by small mode volume photonic structures. The dielectric surfaces that comprise these photonic structures are known to produce electric field noise at the ions that increases heating rates and compromises the fidelity of gate operations for quantum computing. This dielectric induced heating is reduced with decreasing temperature which motivates cryogenic ion-cavity systems.

We report on the design and characterization of a closed cycle 4K flow cryostat that enables rapid prototyping on the integration of a high-finesse Fabry-Perot cavity with a blade Paul trap. We present measurements of the vibrations of the cryostat and an estimate of the vacuum pressure using trapped Yb^+ ions.

A novel trapped-ion system with low-crosstalk individual optical addressability for large-scale quantum simulations

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Our next-generation quantum processor *Bloodstone*, expected to soon trap its first Yb^+ ions, is designed to feature a wide range of exciting capabilities. The segmented blade electrode architecture paired with an XHV capable chamber was engineered for >30 qubits simulations. We will incorporate individual Raman addressing in addition to low-crosstalk in situ mid-circuit measurements and resets using optical Fourier holography [1]. Two 0.5 NA and two 0.3 NA imaging paths aim for rapid and high-fidelity state detection. Our rigorously engineered and modular system will include full-stack controls at various abstraction layers. Once complete, our focus will lie on simulations such as measurement-induced phase transitions.

[1] S. Motlakunta *et al.*, Nature Communications (2024)

Polarisation-Insensitive State Preparation for Hyperfine Qubits

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Electronically driven operations offer a scalable approach to trapped ion quantum computing since the technology is cheap, reliable, and provides stable phase and amplitude control. Using a $^{43}\mathrm{Ca}^{+}$ hyperfine "clock" qubit, we demonstrate a **single-qubit gate error of $\mathbf{1.59(40) \times 10^{-7}}$** with a gate duration of 13.2 μs, which is an order of magnitude lower gate error than the previous state-of-the-art across all quantum computing platforms.
However, due to the rich level structure of ion species with nuclear spins $I > 1/2$, state preparation often requires high-purity circularly-polarised light, complicating the use of integrated optics. Here, we present a hybrid optical/microwave scheme that uses frequency selectivity rather than polarisation selectivity. We demonstrate a **state preparation error of $\mathbf{7.5(13) \times 10^{-4}}$** in 750 μs, achieving high fidelity without stringent polarisation requirements [1].

[1] A. D. Leu *et al.*, arXiv:2406.14448, (2024)

Novel drive-through scheme for scaling up trapped-ion quantum computing

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We introduce a novel drive-through scheme that entangles a stationary ion qubit with a continuously moving ion. Unlike conventional quantum charge-coupled device (QCCD) methods, this approach ensures uniform ion motion, thereby reducing heat generation and enhancing both efficiency and cost-effectiveness in quantum operations. Theoretical demonstrations show gate errors on the order of 10^{-4} with current technology. In this scheme, stationary trapped ion arrays serve as memory units, while mobile ions function as information carriers, enabling long-distance entanglement for achieving scalable quantum computing.

Learning and Mitigating Quantum Errors using Process Tomography of a “Proxy” Qubit

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We develop a new technique for error mitigation in quantum control. We consider a quantum system with large Hilbert space dimension, e.g., a qudit or a multi-qubit system and construct two $2-$ dimensional subspaces — a code space, $\mathcal{C}_q = \text{span}\{|\bar{0}_q\rangle, |\bar{1}_q\rangle\}$ where the logical qubit is encoded and a “proxy” space $\mathcal{C}_p = \text{span}\{|\bar{0}_p\rangle, |\bar{1}_p\rangle\}$. While the qubit (i.e., $\mathcal{C}_q$) can be a part of a quantum circuit, the proxy (i.e., $\mathcal{C}_p$) remains idle. In the absence of errors, the quantum state of the proxy qubit does not evolve in time. In the presence of errors, under reasonable assumptions regarding their generators, the error channel $\mathcal{E}_q$ acting on the logical qubit can be inferred from the error channel $\mathcal{E}_p$ acting on the proxy qubit. The latter can be measured while the qubit is a part of a quantum circuit because, one can perform simultaneous measurements on the logical and the proxy qubits. We use numerical data to learn an *affine map* ϕ such that $\mathcal{E}_q \approx \phi(\mathcal{E}_p)$.

Distributed Quantum Computing across an Optical Network Link

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We present results from our demonstration of distributed quantum computing between two photonically interconnected trapped-ion modules, separated by $\sim 2\,\mathrm{m}$ [1]. Each module contains dedicated network and circuit qubits. Using heralded remote entanglement between network qubits, we deterministically teleport controlled-Z gates between circuit qubits in separate modules, achieving 86.1(9) % fidelity. We then perform distributed quantum circuits comprising multiple instances of quantum gate teleportation, including the execution of Grover’s search algorithm – the first implementation of a distributed quantum algorithm – measuring a 71(1) % success rate.

[1] D. Main, *et al.* Preprint at `https://arxiv.org/abs/2407.00835`.

A Three Dimensional Monolithic Ion Trap for Quantum Simulation and Computation

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Our work focuses on improving the core of trapped ion technology, the ion trap, by combining the features of scalability, repeatability and geometrical accuracy of precision microfabrication with the features of macroscopic three-dimensional traps. We report on the latest developments in the design and characterization of a novel monolithic, segmented 3D ion trap, manufactured by Translume Inc., tested in collaboration with groups at Rice and Duke University to ensure its repeatability. We will discuss our characterization measurements on the axial and radial collective motional modes of a trapped Yb^+ ion, residual micromotion in the trap, and the trap's thermal performance.

Quantum Logic via Electric-field Gradients on Molecular Ion Qubits

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Molecular ions possess a myriad of electric dipole transitions, many of which exist in the microwave and RF regime. These transitions allow for strong, laser-free coupling between long-lived energy states, making them favorable quantum logic candidates. Previously described in ([1]), applying an oscillating voltage to a linear ion trap will produce an electric gradient to address these splittings, allowing for the application of electric-field gradient gates (EGGs). Presented is a description of our cryogenic dual species ion trap employing co-trapped HCl+ and Ca+ in addition to the current progress towards using EGGs to perform hyperfine spectroscopy of the ground lambda-doublet states of HCl+.

[1] PhysRevA. 2021, 104, 042605

State Matching Benchmark on an Ion Trap Quantum Computer

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Characterization of noise via benchmarking procedures is an important part of the development of large scale quantum computers. Most algorithms involve a randomization method, which may average out errors from systematic drift over time, as well as state dependent errors. In order to analyze this noise, a protocol that determines if an unknown quantum state falls into a certain radius of a reference state is implemented. We demonstrate this benchmark on a trapped ion quantum computer for different circuits with different probabilities for successful state matching. Two tests were designed to be sensitive to a wide array of errors, one that assumes invariance to the initial phase of the input state and the other that changes with latitudinal position of the state on the Bloch sphere. [1].

[1] A. Ortega *et al.*, 2023 Phys. Scr., **98** (2023)

Comparing Cavity Enhanced Heralded Entanglement Protocols

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Virtually every proposal for scaling quantum processors requires connecting distributed devices via ‘flying’ photonic qubits. While single-photon protocols have shown promise on other quantum platforms, trapped ion (TI) experiments have seen the most success with *two photon* schemes which probabilistically herald entanglement after interfering photons at a central beamsplitter. The current TI state-of-the-art succeeds at $\sim 250\text{s}^{-1}$[1], an experimental feat but still sluggish compared to most other device operations. Roadmaps to improve this rate often call for optical cavities to dramatically improve photon collection statistics. Here, we ask if and when access to such cavities might also shift the paradigm and make one-photon protocols advantageous for TI systems. For several types of photonic qubits, we compare one- and two-photon protocol limitations on fidelity and rate when subjected to identical mirror fabrication and optical coating constraints.

[1] J. O’Reilly *et al.*, arXiv preprint arXiv:2404.16167 (2024)

Fast photon-mediated entanglement of continuously-cooled trapped ions for quantum networking

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We entangle two co-trapped atomic barium ion qubits by collecting single visible photons from each ion through in-*vacuo* 0.8 NA objectives, interfering them through an integrated fiber- beamsplitter and detecting them in coincidence. This projects the qubits into an entangled Bell state with an observed fidelity lower bound of $F > 94\%$. We also introduce an ytterbium ion for sympathetic cooling to remove the need for recooling interruptions and achieve a continuous entanglement rate of 250 s^{-1}.

Trapped-ion motional SU(2) and SU(1,1) interferometers with sensitivities near the Cramér-Rao bound

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We experimentally implement circuits of one and two mode operations on two motional modes of a single trapped ion. The required displacement, squeezing, and beamsplitter operations are implemented with oscillating electric potentials applied to the trap electrodes which result in electric fields that drive the modes resonantly or parametrically without optical forces. We then implement SU(2) and SU(1,1) [1] interferometers with phase sensitivities near the Cramér-Rao bound. We report phase sensitivities within 0.67(5) dB of the standard quantum limit (SQL) for the SU(2), and 5.9(2) dB and 4.5(2) dB below the SQL for single and two-mode SU(1,1) respectively [2].

[1] B. Yurke, S. L. McCall, and J. R. Klauder, Phys. Rev. A 33, 4033 (1986)

[2] J. Metzner, A. Quinn, S. Brudney, I. D. Moore, S. C. Burd, D. J. Wineland, and D. T. C Allcock, arXiv, 2312.10847 (2024)

Polarization-preserving light storage of 780 nm photon entangled with ^{138}Ba^{+} in warm ^{87}Rb atomic vapor using EIT

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Practical implementation of quantum networking requires interfacing hybrid quantum systems. Trapped ions, which excel at high-fidelity processing with single- and two-qubit gates [1], may be interfaced with neutral-atoms, which excel at single-photon manipulation. To photonically interface ^{138}Ba^{+} and ^{87}Rb, we generate 780 nm photons that are polarization-entangled with the ion. The 780 nm photons are generated using quantum frequency conversion of 493 nm emitted by the ion [2]. Here, we outline polarization-preserving storage and on-demand retrieval of photons from a ^{138}Ba^{+} ion using EIT in a warm ^{87}Rb vapor-cell quantum memory. This work enables temporal network synchronization and enhanced two-node entanglement rates [3].

[1] C. M. Löschnauer *et al.* arXiv:2407.07694 (2024)

[2] J. Hannegan *et al.*, Phys. Rev. A, 106:042441 (2022)

[3] J. Hannegan *et al.*, Phys. Rev. A, 103:052433 (2021)

Developments towards quantum logic spectroscopy for high-precision CPT symmetry tests in a cryogenic Penning trap

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The BASE collaboration tests CPT symmetry by high-precision measurements of the g-factor of (anti-)protons in cryogenic Penning traps [1]. At BASE Hannover an alterantive approach based on sympathetic cooling and quantum logic spectroscopy using ^{9}Be^{+} both as cooling and logic ion is being developed [2].

This poster will present recent advances, including adiabatic transport in the ms-regime and ground-state cooling of a single ^{9}Be^{+} ion [3], as well as upcoming changes to the experimental apparatus.

[1] C. Smorra *et al.*, Nature 550, **371** (2017)

[2] D. J. Wineland *et al.*, J. Res. NIST **103**, 259-328 (1998)

[3] J. M. Cornejo *et al.*, arXiv:2310.18262 (2023)

ORNL Ion Trap Program Overview

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Trapped ion quantum platforms are robust, well-controlled, and well-understood quantum information science (QIS) platforms [1]. For example, these devices have been used to simulate spin chains to probe magnetic phase transitions and execute digital quantum algorithms for simulations in multiple science domains. With the onset of quantum computers that can run small algorithms, domain scientists have begun testing the efficacy of these devices to deliver useful scientific results, driving strong demand for quantum computers and simulation devices. With multiple quantum computer programming stack development, algorithm development, benchmarking, simulation, computation, sensing, and general quantum computer science projects all started within the last several years at ORNL, demand for quantum resources on-site is rapidly expanding.

[1] C. D. Bruzewicz *et al.*, Applied Physics Reviews **6**, 021314 (2019)

Quantum-Limited Detection and Special Relativity: Improving the Electron Magnetic Moment Measurement by a factor of 10

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The most precise test of the Standard Model is the comparison of the measured [1] and predicted values of the electron's magnetic moment [2]. The measurement is performed through detecting the image charge of a single electron using a sensitive detector. We aim to couple the electron to a quantum-limited detector (SQUID), reducing its temperature by a factor of 20. In this new detection scheme, we aim to non-destructively readout the relativistic mass shift due to changes in the particle's cyclotron and spin states. The SQUID amplifier and its enabling technologies– a low fringe field superconducting solenoid and superconducting shield, will be discussed. These new techniques should enable a tenfold improvement in measurement precision and will test the Standard Model at unprecedented precision.

**supported by NSF, SQMS DOE center, and the Templeton Foundation*

[1] X. Fan *et al.*, Phys. Rev. Lett. **130**, 071801 (2023)
[2] R. H. Parker *et al.*, Science **360** 6385 (2018); L. Morel *et al.*, Nature **588** 7836 (2020); T. Aoyama *et al.*, Atoms **7.1** (2019)

Qubit-controlled non-trivial mechanical states in strongly coupled hybrid quantum system

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Quantum states of motion lie at the heart of delivering the promises of the second quantum revolution. Recent experimental developments in quantum optics, opto-mechanics, and superconducting circuits offer exciting opportunities to leverage mechanical modes for applications like quantum information processing, quantum sensing, and quantum transduction. To harness the unique features of mechanical modes in the quantum regime — such as long-lived modes, inherent non-linearities, and compact physical size — the preparation and control of non-trivial mechanical states is critical. In our work, we consider a collection of qubits coupled to an optomechanical system, including a mechanical oscillator and an optical cavity. Specifically, we explore the non-trivial mechanical states in the strong coupling regime of the hybrid quantum system, characterized by significant Wigner negativities and quantum Fisher information. We find that the non-Gaussian characteristics of the mechanical modes can be enhanced by tuning the number of qubits, qubit frequencies, and encoded phases, which also contribute to the robustness of the system in the presence of weak dissipation. These non-trivial quantum states of motion facilitated by our system will be extremely important for improved metrological and state transfer applications.

Hybrid Digital-Analog Simulation of the Yukawa Model using Spin-Phonon interactions

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Simulations of quantum field theories with bosonic fields are resource intensive on fully qubit-based quantum computers due to the infinite-dimensional Hilbert space of a boson. However, trapped ion quantum computers also have motional degrees of freedom which can be used to encode additional information. We experimentally implement a proposal to encode bosonic degrees of freedom in these motional modes [1]. We then simulate the dynamics of a 1+1D Yukawa model using a digital-analog approach: fermionic dynamics are represented with quantum gates, and fermion-boson interactions are represented with spin-phonon interactions mediated by driving a simultaneous red and blue sideband on an ion.

[1] Z. Davoudi *et al.*, Phys. Rev. Research **3**, 043072 (2021)

Pulse Shaping Single Photons from a Trapped Ion with Active Feedback for Hybrid Systems

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Future universal quantum systems will likely leverage the strengths of multiple qubits architectures. Protocols to generate entanglement between subsystems as distinct as a trapped ion and solid-state electron spin qubits typically utilize transduction whereby the state of the matter qubits are mapped onto a pair of photons. Successful entanglement requires that these photons are completely indistinguishable, including the photon temporal profile. We present progress towards demonstrating full arbitrary control for this problem, including optimization of excitation pulse shape, benchmarking of different optimization protocols, and live feedback to control for experimental error. We assert that any emitter can produce photons of any temporal waveform via modulation of the driving Rabi frequency and at most a single π phase change. We discuss future experiments, including interference between a single photon and weak coherent pulse, and remote entanglement of a $^{171}\mathrm{Yb}^{+}$ ion with a ZnO solid-state spin donor qubit.

Progress towards Integration of a High Finesse Optical Cavity with an Individually-Addressed Trapped Ion Chain

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We propose a design which integrates a near-confocal optical cavity with a silicon micro-fabricated surface electrode ion trap with a focus on reproducibility as a different approach to scaling to more ions. We aim to use a high-finesse optical cavity in order to create a fast, coherent, photonic interface between ion chains [1]. This may allow the entanglement of individual spatially separated qubits within one single trap with rates above 10 kHz. Further scaling is possible by using two-photon protocols, potentially employing superradiance, to connect independent cavity-based modules. By using the cavity mode to form an optical lattice, we can suppress the motion of ions along the axial direction. This may allow individual addressing and controlled spin-spin interactions in chains of up to a hundred ions, with applications to quantum simulation, including that of lattice gauge theories.

[1] J. Ramette *et al.*, PRX Quantum, 3, 010344 (2022).

Voltage Solution Generation for Reordering Long-Chain Systems

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We present here on the development and implementation of multi-species trapped ion sorting for a long-chain system. Sorting is performed as part of system initialization to correct for stochastic reordering events caused by background gas collisions [1]. A dual-species chain of 23 ions is loaded into a surface electrode trap. Split and shuttle solutions are generated to isolate arbitrary pairs of ions on which a 2-ion swap operation is performed before chain reconstruction. This nearest-neighbor swap primitive allows for the implementation of a full-chain sort operation using a degenerate bubblesort algorithm. This method was demonstrated on a trapped ion system, enabling dual-species operation for long-chain trapped-ion systems.

[1] Y. Aikyo et. al. *et al.*, Applied Physics Letters 117, **234002** (2020)

Hamiltonian Characterization for Analog Quantum Simulations on a Yb^{+} ion trap

A. Vogliano[1], Y.-T. Chen[1], J. Zhu[1], L. Hahn[1], C.-Y. Shih[1], N. Kotibhaskar[1], S. Motlakunta[1], R. Islam[1]

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Analog quantum simulators use native interactions on well controlled platforms to mimic behavior of uncontrolled systems of interest. Such systems may have complicated Hamiltonians governing their coherent evolution. Verifying the Hamiltonian implemented on the simulator is crucial for the trustworthiness of the simulation's results. Full characterization of a general many-body Hamiltonian is difficult, so here we explore two strategies. The first utilizes a quantum-quench protocol, while the second is a direct measurement of interaction terms, enabled by shelving to auxiliary Zeeman-sublevels. We also explore strategies to use engineered dissipation (delivered via a digital-micromirror-device Fourier hologram) and these shelving tools for opening new classes of quantum simulations, such as dissipative steady-state phase transitions or simulations with time-dependent particle count.

Entanglement with a TEM_{01}-TEM_{00} Raman Transition

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Multi-qubit entanglement within chains of trapped ions is usually created via a spin-dependent push on the normal modes of motion, known as a Mølmer-Sørensen (MS) gate [1]. Many schemes have relied on generating this spin-motion interaction using field gradients parallel to the direction of propagation of counter-propagating lasers in a Raman transition. These schemes are plagued by higher-order motional interactions and off-resonant coupling to the carrier transition. In this poster, we explore using a tightly focused TEM_{01} mode co-propagating with a fundamental TEM_{00} mode to drive an MS gate via the transverse coupling to the motion [2]. Coupling to higher-order motional interactions is controllable by the waist of the beam, and transitions via the carrier resonance are suppressed due to the null electric field in the TEM_{01} mode.

[1] A. Sørensen and K. Mølmer, Phys. Rev. Lett. 82.9, **1971** (1999)

[2] A. West *et al.*, Quantum Sci. Technol. 6(2), **024003** (2021)

Compact acousto-optic deflector individual addressing system for a long-chain trapped-ion quantum computer

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The trapped-ion platform stands out as a highly promising platform for quantum computing due to its longer coherence time compared to other platforms[1], and high-fidelity entangling gates[2]. To achieve a scalable computing architecture with all-to-all connectivity, engineering an individual addressing system with enough addressability is essential. Recent advancements have introduced various techniques for individual addressing, such as the use of MEMS mirrors[2], multi-channel acousto-optic modulators (AOM)[3], and integrated fiber arrays[4].

Here, we present a compact acousto-optic deflector(AOD) based system for an individual addressing of trapped ion. This system offers enhanced addressing flexibility, higher laser power and gate speed, and reduced crosstalk, enabling the implementation of high-fidelity entangling gates in a long ion chain. Our preliminary results show an addressing capability for up to 30 ions with minimized crosstalk between the nearest ions. In addition, our approach utilizes fully customized and miniaturized optical components with minimal control degrees of freedom for maximal optomechanical stability. This unconventional approach results in a compact system with a minimized optical path, which is expected to improve the system robustness to the external mechanical vibrations, highlighting its potential for high-fidelity trapped-ion quantum computing experiments.

[1] Wang, Pengfei, et al. ”Single ion qubit with estimated coherence time exceeding one hour.” Nature communications 12.1 (2021): 233.

[2] Wang, Ye, et al. ”High-fidelity two-qubit gates using a microelectromechanical-system-based beam steering system for individual qubit addressing.” Physical Review Letters 125.15 (2020): 150505.

[3] Kim, Junki, et al. ”Hardware design of a trapped-ion quantum computer for software-tailored architecture for quantum co-design (staq) project.” Quantum 2.0. Optica Publishing Group, 2020.

[4] Mehta, Karan K., et al. ”Integrated optical multi-ion quantum logic.” Nature 586.7830 (2020): 533-537.

3 Poster Abstracts - Session 2 - Thursday Aug 15th, 4pm

Quantum Averaging for High-Precision Quantum Logic Gates

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Analytical modeling of physical realizations of quantum logic gates is explored through a two-timescale quantum averaging theory (QAT). The theory combines the unitarity-preserving Magnus expansion with the method of averaging on Hilbert spaces to address the simultaneous presence of fast and slow timescales ubiquitous in driven quantum systems. To accurately model the system, QAT generates an effective Hamiltonian for the slowly-varying interactions while fully retaining detailed high-frequency dynamics in a dynamical phase. The efficacy of the method is demonstrated with the fast-entangling Mølmer-Sørenson gate, highlighting its potential for identifying and mitigating sources of gate error for high-precision quantum computation.

Quantum Computing on Long Ion Chains

Debopriyo Biswas, Vivian (Ni) Zhang, Yichao Yu, Keqin Yan, Bahaa Harraz, Alexander Kozhanov, Crystal Noel, Chris Monroe

Duke University, Duke Quantum Center

Trapped ion quantum computers feature high connectivity and gate fi
with universal control, and have been used to simulate quantum many-
physics, run medium-sized circuits, and investigate scaling challenges, a
other uses. Here, we present progress towards running gates on a
generation quantum computer with full control of up to 32 $^{171}\mathrm{Yb}^+$ ion q
We use 355-nm individually addressed Raman beams to implement u
rotations and characterize state-preparation-and-measurement (SPA
rors, qubit coherence times, heating rates, vacuum pressure, and fide
operations. Specifically, we present progress towards improving ou
qubit gates, which involved precise alignment of Raman light beam
control of motional modes, and suppression of electrical noise whic
heat or dephase these modes. Preliminary data suggests two-qubit fide
$> 0.985(2)$ in a 5-ion chain, and we discuss challenges and plans for s
to ~ 30 ions. We measured ion heating rates and motional dephasin
calculated their expected contributions to two-qubit gate errors. The
ware upgrades compared to previous systems should lead to higher fi
gates and expand the complexity of physics that we can simulate wit
quantum computer.

Progress toward quantum networking with $^{40}\mathrm{Ca}^+$ ions in a cryogenic surface-electrode trap with an integrated fiber cavity

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Distributing entanglement over a quantum network has the potential to enhance quantum sensing, improve communication security, and distribute quantum computational power. Trapped ions are a promising memory qubit for the nodes of such a network due to their long coherence time, precise state preparation and control, high-fidelity two-qubit gates, and ability to be entangled with emitted photons. Using an optical cavity can provide high photon collection efficiency, but also brings the ion and laser beams close to the dielectric cavity mirrors, which could lead to increased motional heating and stray charge accumulation. Here we will present our design for a cryogenic surface trap with an integrated fiber-based optical cavity, and our progress characterizing the behavior of $^{40}\mathrm{Ca}^+$ ions hundreds of microns from unshielded optical fibers.

Cryogenic operation of micron-scale 3D-printed ion traps

M. Brzeczek[1], R. Kwapisz[1], A. Sawhney[1], N. Kuvvet[1], C. Zhang[1], S. Xu[2], H. Dan[1], V. Baid[1], D. Li[1], S. W. Buechele[1], R. A. Ready[1], X. Xia[3], K. Beck[3], J. Biener[3], B. Hemmerling[4], H. Haeffner[2], D. Patterson[1], A. M. Jayich[1]

[1]University of California, Santa Barbara, [2]University of California, Berkeley,
[3]Lawrence Livermore National Laboratory, [4]University of California, Riverside

We are working with the first horizontal micro-3D ion traps fabricated with the two-photon polymerization 3D-printing process. This fabrication method supports complex trap structures and holds promise for ion motional operations and integrated photonics compatibility. To characterize these traps, we designed a cryogenic system optimized for efficient prototyping of 3D-printed trap designs. We have trapped Sr^+ crystals, measured secular frequencies, and performed spectroscopy on the trapped ions. We are working on measuring the dependence of motional heating rates on the secular frequency and trap location. Future work will focus on trap design improvements and eventually extend to shuttling and quantum logic operations.

Thermally Stable Optical Reference Cavity Utilizing Composite Materials

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We constructed an optical reference cavity with a very low effective Coefficient of Thermal Expansion (CTE) using a cavity spacer made from readily accessible composite materials. These materials were joined in such a way that their overall thermal expansions canceled out, yielding an effective CTE lower than that of the individual materials. The residual effective CTE can be further compensated towards zero by tuning the pressure, and thus the intra-cavity refractive index, of the filled gas. By combining these two mechanisms, we reduced the effective CTE of the cavity to below 10^{-7}/K. This simple cavity can serve as a thermally stable reference for laser frequency stabilization.

Advancing Chip-Trap Quantum Computing with Barium Ions

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Multiple Yb-based trapped-ion quantum computing systems are currently being operated at Duke Quantum Center. Here we present the progress on the construction of Ba^+ ion based 100+ qubit multi-core quantum computing system. A Peregrine chip trap by Sandia National Laboratory[1] is used to trap multiple ion chains simultaneously. Ba ions allow using visible 532nm individually addressing beams to execute Raman qubit gates on several chains. The trap is operated at cryogenic temperatures promising low heating rates and long ion chain lifetimes. Mid-circuit measurements using ion shuttling and *omg* architecture are being implemented.

[1] M. C. Revelle, arXiv: 2009.02398 (2020)

Quantum testbeds for advancing hardware: a QSCOUT story

S. M. Clark[1,2], A. D. Burch[1], M. N. H. Chow[1,2], A. Christensen[1], J. Goldberg[1], M. Ivory[1], A. J. Landahl[1,2], D. S. Lobser[1], B. K. McFarland[1], B. C. A. Morrison[1,2], T. Redhouse[1], M. C. Revelle[1], K. M. Rudinger, A. E. Russo[1], B. P. Ruzic[1], J. W. Van Der Wall[1], and C. G. Yale[1]

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The Quantum Scientific Computing Open User Testbed (QSCOUT) based at Sandia National Laboratories is a “white box” quantum processor based on trapped ions available to the scientific community as of 2021 [1]. During the process of running user code, we encountered numerous unforeseen challenges, resulting in hardware improvements to the machine for the next round of experiments. I will present how working with user teams—and the testbed model in general—has accelerated progress in gate implementation and calibration, software, and classical control hardware. SNL is managed and operated by NTESS under DOE NNSA contract DE-NA0003525

[1] https://qscout.sandia.gov

Magnetic Field Noise Mitigation With *omg*

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Quantum computers require extensive, time-consuming recalibration procedures to maintain high-fidelity operations. We present progress towards live parameter tracking that can be performed in parallel with data storage or computing operations. We implement the protocols on $^{40}\text{Ca}^+$ ions, storing data in the ground state qubit and using multiple levels of the metastable excited state to measure magnetic field drifts. By using omg-inspired primitives [1], the "monitor ion" operations will not introduce crosstalk on the data qubits. We demonstrate magnetic field tracking using a monitor ion, and predict future fidelity gain when used with data qubits.

[1] D. T. C. Allcock, *et al.* "omg blueprint for trapped ion quantum computing with metastable states." Appl. Phys. Lett. 119.21 (2021).

Progress on Software-Tailored Architecture for Quantum Computing (STAQ) Hardware and Control

M. Donofrio[1], S. Phiri[1], A. Van Horn[1], T. Chen[1], J. Whitlow[1], A. Dalvi[1], T. Hurant[1], J. Kim[1], K. R. Brown[1]

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Cryogenic traps are desirable for longer lifetimes and lower heating rates, but new conduits for noise are introduced by cryostation electronic complexity. We address low-frequency noise injection from the cryomotor by introducing a compact 4K rf delivery system and sapphire spacers between the first and second cooling stages. This electrically isolates the coldfinger and trap voltage lines, bypassing noise injected at the pump while maintaining cryogenic temperatures. We also work to maintain accurate system control parameters while spending little time on calibration. Using the DAX scheduler [1], we automate background processes that trigger graph-based recalibrations via subroutines. We explore quick characterization checks both informed enough to determine sub-routines and cheap enough to demonstrate advantage over full calibration. Use of a classical simulator as a virtual twin of the quantum system is also explored to inform calibrations.

[1] L. Riesebos et al., IEEE Micro 41.5 (2021)

Toward a System for Studying Trapped-Ion Phononics in a Dual-Species Ion Chain

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We are constructing an experimental apparatus to perform quantum simulation of nanoscale heat transfer, using a chain of co-trapped Ca^+ and Sr^+ ions as a playground to manipulate and control heat flow in a way analogous to existing technological control over electrical currents. Such experiments require large cooling rates on particular ions to effectively simulate thermal reservoirs. To this end, we are implementing EIT cooling and sideband thermometry of both ion species. We aim to demonstrate a well-controlled system for investigating heat currents while also informing future simulation studies which rely on laser-cooling of motional modes along an ion chain.

A Site-Resolved 2D Quantum Simulator with Hundreds of Trapped Ions

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We report the stable trapping of 512 ions in a 2D Wigner crystal and the sideband cooling of their transverse motion. We demonstrate the quantum simulation of long-range quantum Ising models with tunable coupling strengths and patterns, with or without frustration, using 300 ions. Enabled by the site resolution in the single-shot measurement, we observe rich spatial correlation patterns in the quasi-adiabatically prepared ground states, which allows us to verify quantum simulation results by comparing with the calculated collective phonon modes and with classical simulated annealing. We further probe the quench dynamics of the Ising model in a transverse field to demonstrate quantum sampling tasks. Our work paves the way for simulating classically intractable quantum dynamics and for running NISQ algorithms using 2D ion trap quantum simulators.

Updates on the PTB two-qubit quantum processor

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The QVLS collaboration aims to build a 50 qubit quantum computer based on trapped ions by 2025. In the existing two-qubit quantum processor we have already shown the demonstration of arbitrary quantum circuits on ^{9}Be$^+$ ions [1] by using microwave conductors embedded in the trap [2]. The poster will show these results and the developments that happened in the laboratory since then. These include changes of experimental hardware, software and progress towards a cloud interface.

[1] N. Pulido-Mateo *et al.*,Physical Review Research 6, **2** (2024)

[2] C. Ospelkaus *et al.*,Nature 471 **7337** (2011)

A New Generation $^{27}Al^+$ Optical Clock

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The $^1S_0 -^3 P_0$ transition in $^{27}Al^+$ is a precise frequency standard thanks to its narrow linewidth and insensitivity to environmental perturbations, yet ion clocks have limited stability due to quantum projection noise. NIST's previous Al^+ quantum logic clock reached a systematic uncertainty below 10^{-18} and a stability of $1.2 \times 10^{-15}/\sqrt{\tau}$ with a single ion [1]. Upgrades to NIST's Al^+ clock apparatus are tailored for multi-ion operation, including a larger, more homogeneous ion trap and an improved vacuum system. This will enable clock spectroscopy on multiple Al^+ without sacrificing systematic uncertainty or clock uptime. This poster reports on the next generation NIST Al+ clock apparatus and progress toward multi-ion operations.

[1] Brewer, Samuel *et al.*, Physical Review Letters . 123.3 , (2012)

Progress toward measurements of piezoelectric resonances with trapped ions

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Coupling trapped ions to well controlled "macroscopic" degrees of freedom can provide novel ways of sensing or controlling the outside world [1, 2]. For instance, the electrically mediated coupling between the phonon modes of a trapped ion and a nearby bulk piezoelectric resonator (piezo) could prove useful for applications in vibrational sensing or quantum communications. Here we present a planned experiment that serves as a first step, aiming to measure the resonant heating of a laser cooled ytterbium ion in close proximity to a room temperature piezo. This poster highlights the chamber design for co-locating the ion and piezo along with our recent work building, designing, and testing our trapping infrastructure.

This work is supported by NSF Grant No. 2309243

[1] W. K. Hensinger *et al.*, Phys. Rev. A, 72, **041405** (2005)

[2] D. De Motte *et al.*, Quantum Inf. Process. 15, **5385** (2016)

High-Efficiency Optical Frequency Offset

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We demonstrate an optical frequency offset (OFO) by serrodyne modulation using a fiber EOM and radio-frequency (RF) tones from a commodity RF system on a chip. We achieve shifts between 40 MHz to 800 MHz with $>$ 15 dB suppression of spurious sidebands and $<$ 1.5 dB conversion loss. The utility of our tool is demonstrated by continuously shifting the offset of a cavity-locked laser from 50 MHz to 1600 MHz. We discuss the limitations of this approach and present a comparison to other known methods of achieving an OFO. Additionally, we consider its application to spectroscopy experiments searching for narrow optical transitions.

Fabrication and characterisation of microlens arrays for scalable ion trap cooling, addressing and readout

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To achieve fault tolerant quantum computing with trapped ions, many architectures demand the engineering of high-performance systems that are manufacturable at scale. Control of trapped ions requires numerous light fields, typically delivered with bulk optical systems. These introduce significant overhead for alignment, have sizeable footprints and are susceptible to long term drifts. To address the challenge of scalability, we have developed refractive microlens arrays intended to encompass all optical functionality required for ion cooling, coherent control and readout. We present the method and results in the characterisation of these wafers, chiefly comprising of high-precision beam profilometry and surface mapping. We further present the theoretical considerations which underpin the optimal design of such arrays, including an overview of the system being integrated into our future ion-cavity network architecture.

Quantum logic spectroscopy of a single $\mathbf{H_2^+}$ molecular ion

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I will present our latest results, implementing pure quantum state preparation, coherent manipulation, and non-destructive state readout of a single hydrogen molecular ion H_2^+ using quantum logic spectroscopy. We trap a single H_2^+ molecule together with a single beryllium ion using a cryogenic Paul trap apparatus, achieving trapping lifetimes of 11h and ground-state cooling of the shared axial motion [1]. We utilize helium buffer-gas cooling to prepare the lowest rovibrational state of ortho-H_2^+ (rotation $N = 1$, vibration $\nu = 0$). We combine this with quantum-logic operations between the two ions for preparation of single hyperfine states and non-destructive readout, demonstrating Rabi flopping on several hyperfine transitions.

[1] N. Schwegler, D. Holzapfel, M. Stadler, A. Mitjans, I. Sergachev, J. P. Home, and D. Kienzler, Phys. Rev. Lett. **131**, 133003 (2023)

Towards ultracold atoms/molecules through photodissociation of sympathetically cooled molecular ions

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Ultracold atoms and molecules are fundamental building blocks of quantum science, yet the workhorse technique - direct laser cooling - is out of reach for the vast majority of chemical species. To increase the chemical diversity of ultracold species, we propose to generate ultracold "fragments" through near-threshold photodissociation of sympathetically cooled molecular ions. Here we discuss methods to sympathetically cool alkaline earth metal molecular ions (MX^+) within a coulomb crystal. Near threshold photodissociation of these cold MX^+ can produce ultracold fragments which can then be trapped in a conservative potential for further analysis. The fragments' low external kinetic energy and high degree of quantum state specificity make them excellent candidates for state-to-state collision/reaction studies and precision spectroscopy. Finally, we discuss the applications of this method to generate specific ultracold species, like atomic hydrogen and hydrocarbon radicals.

Development of Enhanced Fabrication Processes for Suppression of Semiconductor Charging and Chip with Arbitrary Outline

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Ion trap chips fabricated using silicon processes benefit from multi-layer fabrication, enabling scalable trap architectures and the integration of optical components through silicon photonics. Despite challenges such as shallower trap depths, susceptibility to dielectric charging, and higher heating rates compared to macroscopic traps, these devices continue to be a focus of active research. In this study, we developed new fabrication processes to mitigate silicon charging effects by applying a gold coating to exposed silicon areas. Additionally, we have redesigned the chip's outline with arbitrary shapes to minimize laser scattering. Experimental results confirm that these modifications significantly enhance the performance of the chip, representing a substantial advancement in chip-based ion trap technology.

Compact and robust optical frequency reference module based on reproducible optical design

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In this work, we present a compact and robust optical frequency reference based on Doppler-free spectroscopy using a Rubidium cell reference. The entire system involves the laser source, optics for spectroscopy, and the control electronics for feedback, and it is modularized into a compact 19" rack-mountable case, ensuring ease of use and robustness against external environmental drift. We measured the Allan deviation of the reference laser to be 3.68×10^{-10}, close to the resolution limit of the wavelength meter. Also, the system demonstrated high resilience of frequency lock against two minutes of external vibration up to 4G. The module is constructed using CAD design derived from optics-based metadata, making it highly replicable and reproducible.

Enhancement of quantum operations in a silicon chip protected from semiconductor charging

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Despite their advantages in scalability, silicon-based ion traps can suffer from semiconductor charging, where undesired photogenerated electrons and holes produce an electric potential that displaces the ion. Based on our recent study on the charge distribution mechanism in semiconductors and its effect on quantum operations of trapped ions [1], we have fabricated a new silicon-based chip with protective gold coating on all exposed silicon surfaces. We observed that the drift or fluctuation of vibrational mode parameters associated with background silicon-induced fields were removed by orders of magnitude. Consequently, the improved chip enabled effective sideband cooling and two-qubit entangling gates, both of which were not achievable in the previous chip lacking any protective gold layers.

[1] W. Lee *et al.*, Phys. Rev. A. 109, 043106 (2024)

Experimental Implementation of Single-shot Joint Parity Measurement for Quantum State Tomography of Phonon Modes

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We have implemented a single-shot joint parity measurement of two motional modes of a trapped ion using spin-dependent beam splitter (SBS) interaction [1]. This approach enables direct measurement of the joint Wigner function of a two-mode entangled coherent state [2], with reduced measurement time and without the need for data fitting. By applying bichromatic laser fields, we induced SBS interactions and measured the joint Wigner function on several planes in the 4D phase space. Our experimental results, which show good agreement with theoretical predictions, demonstrate the feasibility of this method for efficient quantum state tomography in bosonic dimension of trapped ion system.

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[1] C. H. Nguyen *et al.*, arXiv:2013.10219v1 [quant-ph] (2021)

[2] H. Jeon *et al.*, Sci. Rep. **14**, 6847 (2024)

Raman transition of ^{171}Yb^{+} via Optically Phase-Locked Lasers

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We present the Raman transitions of a trapped Yb ion qubit using a pair of continuous-wave (CW) lasers. Our laser system consists of two frequency-tripled fiber lasers, where the seed lasers have a wavelength of 1108nm and are optically phase-locked to have 4.2GHz frequency difference. With the phase-locked 369.7nm frequency-trippled beams, we successfully realized co- and counter-propagating Raman transition of single $^{171}Yb^{+}$ hyperfine qubit with the phase-locked laser beams. Lastly, we present our latest work on the design and characterization of individual addressing optics using a multi-channel acousto-optic modulator[1].

[1] S. Lim *et al.*, Optics & Laser Technology 180, 111436 (2025).

A Single-Ion Information Engine for Charging Quantum Battery

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An information engine converts information into useful mechanical work or energy through a cyclic process, analogous to heat engines. One major challenge in realizing cyclic information engines in quantum systems arises from the measurement disturbance problem. We report the experimental implementation of a quantum version of the information engine using a single trapped ion in a mechanical oscillator by significantly suppressing the effect of measurement disturbance. The measurement of the internal state of a single ion becomes a source of work, increasing the energy of its mechanical oscillator, which serves as a quantum battery and can be read out through phonon-number-resolving detection. Our device provides a seminal model of a quantum information engine, enabling us to explore and utilize the fundamental nature of quantum information and thermodynamics.

Shuttling-based Distributed Quantum Computing Architecture and Camera-based State Detection

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Here, we study the shuttling-based distributed quantum computing (SDQC
architecture, which integrates shuttling and distributed quantum computing
SDQC comprises multiple ion chains with fixed data qubits where interchai
entangling gates are mediated by entangled communication qubits trans
ported by ion shuttling. Such architectures enable asynchronous operation
between data qubit manipulation and shuttling of entangled qubits. We as
sessed the performance of SDQC in terms of the time cost and effective erro
of remote gates, comparing the result with other scaling approaches. Th
time cost is evaluated for operation run time and entanglement distributio
time, while the number of operations, shuttling loss, and coherence time wer
considered to estimate the effective error. The feasibility of hybrid architec
ture with photonic interconnect and prospects for large-scale systems ar
discussed as well.

We also study low-noise camera-based state detection scheme which can b
used for an arbitrarily shaped ion crystal. We studied the relationship be
tween camera magnification and state detection fidelity and designed th
imaging optics based on such a study. We discuss the proper alignment pro
cess to achieve diffraction limit imaging with an in-cryo lens before coolin
down the cryostat.

The Aharonov-Anandan phase of a spin-J system using detuned beam splitter operations between the motional modes of trapped ions

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Investigating spin-J systems ($J \geq \frac{1}{2}$) is crucial for simulating complex molecules and materials, advancing quantum chemistry and material science. We propose an experimental scheme to observe the non-adiabatic geometric phase, known as the Aharonov-Anandan (AA) phase, in a spin-J system ($J \geq \frac{1}{2}$) using state-dependent detuned beam splitter operations in trapped ions. Two motional modes encode the state of the spin-J system through the Schwinger-boson representation. Beam splitter operations via bichromatic beams near sidebands enable effective SU(2) rotations. Numerical simulations show that detuned beam splitters exhibit the geometric phase through parity oscillations.

[1] E. Layton et al, Phys. Rev. A 41, **42** (1990)

Development of a Room-Temperature Trap for Hundreds of Two-Dimensional Ions

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We have developed a monolithic trap with laser-machined alumina and demonstrated loading, cooling, and quantum simulation with 2D stationary ion crystals [1, 2, 3]. However, in the room-temperature vacuum chamber, the performance of the alumina trap in increasing the number of trapped ions was limited by mainly large heating rates [2, 3]. Here, we have developed a novel monolithic trap using femtosecond laser-based 3D printing on fused silica to overcome the limitations of the alumina trap, which has reduced surface roughness by an order of magnitude. With the trap, we were able to stably trap hundreds of crystallized ions.

[1] Y. Wang *et al.*, Adv. Quan. Techonol. 3, 2000068 (2020).

[2] M. Qiao *et al.*, Phys. Rev. Lett. 126, 023604 (2021).

Optical frequency stabilization via optical cavity and stable RF reference

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Laser frequency stabilization is ubiquitous in spectroscopy and AMO (atomic, molecular, and optics) experiments. While Pound-Drever-Hall (PDH) method can be employed to lock a laser frequency to the cavity resonance frequency, the cavity length is typically subject to thermal drift. Here, we introduce a technique for stabilizing the laser frequency with the absolute frequency target, using only a single target laser modulated by a stable RF reference. The feedback signals regarding the laser and cavity length are obtained from the reflection and transmission signals of the cavity, respectively, and the target frequency can be changed by merely altering the RF reference frequency. We analyze the impact of parameters on error signals and assess the lock performance to identify the most suitable parameters required.

Full-Stack Real-Time Control System and Microwave Gate in Trapped Ion Quantum Computer

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A Real-Time control system is essential for trapped ion quantum computer. We built an FPGA-based control system using ARTIQ for ns-precision synchronized control. Using the DAX(Duke ARTIQ Extensions) library, we implemented modular control software [1]. We built the full-stack software architecture with the QisDAX library, which bridges the Qiskit and DAX [2]. In this system, we performed microwave gates and measured an average single-qubit gate fidelity of $99.9983 \pm 0.0001\%$ using Direct RB(Direct Randomized Benchmarking).

[1] L. Riesebos, 2022 IEEE International Conference on QEC, p. 545-555 (2022)

[2] K. Badrike, 2023 IEEE International Conference on QEC, p. 825-836 (2023)

Search for a CP Violation in Lutetium molecular ion: Initial Experimental Results of Barium Photoionization and Simulations of Cooling Fluorescence for Trapping Barium [1]

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Lutetium nuclei have a large quadrupole deformation that can give enhanced sensitivity to sources of nuclear CP-violation arising from beyond Standard Model physics. A precision measurement of a molecular ion such as $LuOH^+$ using quantum logic spectroscopy, exploiting the long lifetime and high contrast typical of ion traps, could be a sensitive probe of nuclear CP-violation. We present on a radiofrequency linear Paul trap designed to co-trap barium, lutetium, and $LuOH^+$, and show initial experimental results depicting isotopically selective photoionization and hyperfine splitting of odd barium isotopes by observing the decay from 5d6p $^3D_1$ into metastable states. Additionally, we simulate and depict the cooling fluorescence spectrum of trapped barium.

Latest developments in DI/OT Sinara ecosystem

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Sinara is an open-source, open-hardware control system specifically created for quantum applications that is currently operational in numerous global laboratories. A new system architecture named DI/OT was developed for Sinara, due to concerns about system reliability, thermal managment and effective monitoring. DI/OT is based on the Compact PCI-Serial standard and is a product of collaborative development with CERN. New Sinara modules are currently developed in DI/OT form factor. In this poster, we present latest developments in this system architecture, including new native controller, 32 channel DAC module, current source for DC coils, 10 W RF amplifier with modulator input and low noise frequency reference.

Towards Entanglement of ^{138}Ba^{+} and Telecom Photon via Quantum Frequency Conversion

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Ba ions have been proposed as communication qubits in long-distance quantum networking architectures due to their large dipole branching ratio and ease of ion-photon entanglement generation. To extend the network operating range requires frequency down-converting the Ba ion's 493-nm photon to a telecom wavelength [1]. Here, we report progress towards generating ion-photon entanglement at telecom O-band using two concatenated stages of quantum frequency conversion (QFC) to 1287 nm. Our QFC scheme preserves entanglement between the ion's spin and the photon's polarization, and is projected to significantly improve SNR compared with our previous effort converting to telecom C-band [2].

[1] M. Bock *et al.*, Nat. Commun. **9** 1998 (2018).

[2] U. Saha *et al.*, ACS Photonics **10** 8 (2023).

Integrate photonics control of Sr ions

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Advancements in integrated photonics and micro-scale ion trap fabrication have promise for realizing transportable trapped-ion optical clocks. We demonstrate optical control of a ^{88}Sr^{+} ion with a 1033 nm vernier ring laser. The laser has a 1 MHz intrinsic linewidth and a total footprint of less than 1 mm^2. Using this laser, we performed spectroscopy on the 4^2D$_{5/2}$ to 5^2P$_{3/2}$ transition in a single trapped strontium ion. This transition is critical to clock operation as it returns the ion to the cooling and state detection cycle from the 4^2D$_{5/2}$ clock state. This work is a foundational step towards ion trapping systems with fully integrated addressing lasers.

Precision vibrational spectroscopy of a single molecular ion

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Cold molecules are a novel platform for precision measurement, such as measuring the electron electric dipole moment and exploring possible variation of fundamental constants. Here, we report on spectroscopy of vibrational overtone transitions in a single CaH^+ ion using quantum-logic spectroscopy. After preparing CaH^+ in a single quantum state [1], we efficiently searched and characterized its 4^{th} vibrational overtone with a broadband infrared frequency comb [2], and resolved the spin-rotation structure, reaching below part per 10^{13} statistical uncertainty in frequency. We present a method for efficiently searching for narrow transitions over a large frequency range.

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

[2] Liu *et al.*, arXiv: 2312.17104 (2023)

Deterministic State Preparation and Logical Gate Operations on Gottesman-Kitaev-Preskill Qubits

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We demonstrate a robust, high-fidelity, and measurement-free optimal quantum control protocol to prepare arbitrary bosonic states in the mechanical motion of a trapped ion. We prepare several bosonic logical code words relevant to hardware-efficient bosonic quantum error correction, including the preparation of a Gottesman-Kitaev-Preskill code word with a logical fidelity of 0.940(8) and squeezing of 7.5(2) dB, a distance-3 binomial state with an average fidelity of 0.807(7), and a squeezed vacuum state with 12.91(5) dB of squeezing [1]. We also report recent progress on implementing single-qubit and two-qubit logical gates for GKP qubits.

[1] V. G. Matsos *et al.*, arXiv 2310.15546 (2023)

Progress Towards a ^{229}Th^{3+} Nuclear Clock

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Atomic clocks are the most precise instruments in existence today, with state of the art clocks achieving fractional inaccuracies at the level of 10^{-18}. Atomic clocks work by locking the frequency of a local oscillator to an atomic transition. The precision of an atomic clock is improved with higher frequency clock transitions and transitions which are less sensitive to external perturbations. To develop a next generation clock, it is natural then to seek a clock candidate which has a transition meeting both requirements. The ^{229}Th^{3+} ion offers one such transition, having an anomalously low-energy nuclear isomer transition at 148 nm, just on the edge of what is experimentally achievable with VUV lasers. This transition is very narrow and is insensitive to external perturbations due to the strong suppression of external field-shifts. Experimental progress towards the development of a next generation clock utilizing this ^{229}Th^{3+} nuclear isomer transition will be presented.

Characterization of a Robust Cryogenic Vacuum Chamber for Ion Trapping Experiments

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I describe a newly designed cryogenic vacuum chamber for trapped ions that includes in-vacuum magnetic shielding, an in-vacuum objective with focusing assembly for increased optical detection efficiency, an in-vacuum global RF coil for exciting ground state Zeeman transitions, and reduced vibration coupling to the trap. I show the magnetic field uniformity across the trap via ion coherence times as well as Zeeman and optical qubit spectroscopy. We perform demonstrations of dynamical decoupling with the RF coil, and finally assess the collection efficiency of the optical assembly.

Observing super-quantum correlations across the exceptional point in a single, two-level trapped ion

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Using a dissipative, trapped ^{40}Ca$^+$ ion governed by a two-level, non-Hermitian Hamiltonian, we observe temporal correlation values up to 1.703(4) for the Leggett-Garg parameter K_3, clearly exceeding the hitherto inviolable Lüder's bound of 1.5 [1]. These excesses occur across the exceptional point of the parity-time symmetric Hamiltonian responsible for the qubit's non-unitary, coherent dynamics. Distinct evolution speeds for antipodal qubit states, which violate the unified (Mendelstam-Tamm or Margolus-Levitin) bound for the transit time based on the quantum speed limit τ_{QSL}, result in the super-quantum K_3 values observed over a wide parameter range.

[1] A. Quinn, J. Metzner, J.E. Muldoon, I.D. Moore, S. Brudney, S. Das, D.T.C. Allcock, and Y.N. Joglekar, arXiv, 2304.12413 (2023)

Entangled States of Motion in a Two-Dimensional Ion Microtrap Array

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Two-dimensional arrays of ions trapped in individual, dynamically tunable microtraps are a promising technology for quantum computation and simulation. By controlling the motional excitations of the ions (phonons), one may be able to generate multipartite entanglement between ions trapped in such an array and also simulate complex Hamiltonians. We trap three ^{9}Be$^+$ ions in a surface electrode ion trap that has three confining potential wells 30 µm apart on the vertices of an equilateral triangle. By applying static control potentials, we can individually tune potential curvatures at each trapping site. When site curvatures are nearly equal, the individual ion motional modes hybridize into collective normal modes that we can excite using resolved motional sideband transitions. Here, we report on our progress toward using these collective excitations to entangle the motion of all three ions.

Trapped ion clock and qubit operations with visible integrated photonic laser sources

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Development of a trapped ion system-on-a-chip would require integration of multiple precision optical systems within the surface electrode trap (SET), but could provide passive phase stability and enable scalability for quantum computing and quantum sensing. We report the first optical clock and qubit operations using integrated photonic laser systems operating directly at visible wavelengths[1] which can be readily integrated within SETs. While the initial performance is modest for clock applications, we find that the system is already capable of high fidelity state preparation and measurement for quantum computing applications, and outline how improvements in visible photonics (already demonstrated in the IR), are on track to surpass traditional ULE cavities.

[1] arXiv preprint arXiv:2402.16742.

Progress on the JILA Gen. III eEDM Experiment

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The recently concluded JILA experiment reported the most precise measurement yet of the electric dipole moment of the electron (eEDM), $d_e = (-1.3 \pm 2.0 \text{ stat} \pm 0.6 \text{ syst}) \times 10^{-30}$ e cm, using electrons confined inside molecular ions HfF^+ [1, 2]. The third-generation apparatus at JILA aims to push the limit even more, by taking advantage of the long coherence time of the eEDM-sensitive state ($^3\Delta_1$) of ThF^+, which is the ground state [3, 4, 5]. To fully take advantage of the long coherence time, it is necessary to decouple repetition time of the experiment from the long coherence time. We plan to make a "conveyor belt" of 25 consecutive ion traps, named the Bucket Brigade which will continuously load and read out ThF^+, allowing for an increased duty cycle without compromising long interrogation times. We are currently studying the prototype of the Bucket Brigade, the baby Bucket Brigade. In our prototype experiment, we measure a coherence time of about 8 seconds and report the limiting factors for the coherence time, including blackbody radiation, rotating electric field inhomogeneity, ion-neutral collisions, and ion-ion collisions. We also present our progress towards a continuous-mode precision measurement including measurements of quantum evolution during ion transport.

[1] T. Roussy *et al.*, Science **381** (2023)

[2] L. Caldwell *et al.*, Phys. Rev. A. **108** (2023)

[3] D. N. Gresh *et al.*, J. Mol. Spectrosc **319** (2016)

[4] Y. Zhou *et al.*, J. Mol. Spectrosc **358** (2019)

[5] K. Ng *et al.*, Phys. Rev. A **105** (2022)

Charge Exchange between CaH^+ Molecular Ions and K Atoms

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The development of ion-atom hybrid systems over the past two decades has led to investigations of ultracold chemistry in various combinations of trapped ion-neutral species. Here, we extend the use of hybrid traps, which until recently have mainly been limited to atomic species, to molecular ions. We report on studying interactions between trapped and sympathetically cooled calcium mono-hydride (CaH^+) molecular ions and laser-cooled neutral potassium (K) atoms. We observe charge exchange between the two species and measure the reaction rate coefficient to be $4.42(35)\times10^{-10}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$. Notably, this measured rate is an order of magnitude lower than the Langevin rate for this system. We perform quantum-chemical calculations of the interaction potentials to explain the observed rate and explore the underlying mechanism for chemistry in this polar diatomic molecular ion-alkali atom system.

3D-printed ion traps for scalable quantum information processing

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A 3D-printed trap fabricated at LLNL has recently demonstrated single-ion coherent manipulations, confirming compatibility of materials with ion-trap quantum hardware [1]. In spite of impressive performance metrics, the trap design is not scalable. In this poster, we describe our effort towards setting up an ion trapping experiment to explore scalable 3D-printed ion traps. Millimeter-scale traps have been printed at LLNL with their axis parallel to the trap substrate. In conjunction with dc control-electrodes on the surface, these traps will enable ion transport operations for the QCCD architecture. In the near term, we will benchmark the performance of the printed ion traps with a trapped $^{40}Ca^+$ ion.

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[1] S. Xu, X. Xia *et al.*, arXiv:2310.00595v2 (2023).

Apparatus design for scalable cryogenic quantum computing experiments based on trapped-ions

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Future applications for trapped ion quantum computers require a significant increase in the number of ion qubits and excellent interconnectivity. In my poster, I outline the design of cryogenic demonstrator machines that incorporate surface-electrode ion traps mounted on a universal interchangeable socket. The core design features a vibration-isolated cold head, which efficiently cools a cryogenic vacuum system to temperatures below 10 K. The system includes several hundred DC control lines to facilitate qubit transport through dedicated trap structures, including junctions, storage, detection, and manipulation registers. Multi-qubit quantum gates will be realized using chip-integrated microwave lines. Moreover, the system is adaptable for integrating new components as enabling technologies evolve, such as chip-integrated waveguides. One setup is based on $^{9}\mathrm{Be}^{+}$ qubits and $^{40}\mathrm{Ca}^{+}$ ions for sympathetic cooling; a second setup is based on $^{43}\mathrm{Ca}^{+}$ and $^{88}\mathrm{Sr}^{+}$ ions.

Experimental Observation of Dipole Phonon interaction in CaO^{+} and Ca^{+} ion chain

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The molecular ion dipole can be coupled to the collective motion of co-trapped atomic and molecular ions enabling readout of molecular states by atomic ion fluorescence. In dipole-phonon quantum logic (DPQL), the state of the molecular ion is mapped to the motional state through an adiabatic sweep of the trap frequency [1]. The change in the phonon state is then detected using an atomic ion. We have identified CaO^{+} is an ideal candidate for demonstrating DPQL [2] and present our preliminary observations of DPQL at room temperature.

[1] W. C. Campbell and E. R. Hudson, Phys. Rev. lett. **125**, 120501 (2020)

[2] M. Mills *et al.* Phys. Chem. Chem. Phys. **22**, 24694 (2020)

Sympathetic Cooling and Quantum Simulations on a Compact Cryogenic Setup

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Cryogenic setups can provide more stable operating environments and offer lower motional heating rates compared to conventional ion-trapping experimental systems. However, extension to longer ion chains still leads to the anomalous heating effect due to lower axial confinement [1]. In this poster, I will discuss our compact cryogenic setup and highlight our progress towards sympathetic cooling on multi-isotope ion chains of Ytterbium to mitigate this heating effect. The ability to retain long chains and perform fast 2-qubit interactions using our newly integrated AOD assembly for individual addressing [see poster by J. Yu] makes our experiment an ideal platform for conducting analog quantum simulations on multi-site dissipative spin-boson models.

[1] M. Cetina *et al.*, “Control of transverse motion for quantum gates on individually addressed atomic qubits,” PRX Quantum, vol. 3 (2022)

Simulation Methods for Surface Ion Traps Using Finite Element Analysis

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Using a commercial finite element analysis software, a method for simulating the fields produced by surface ion traps is provided, along with a description of its benefits and limitations. Using the results from these simulations, various aspects of the trap can be determined (secular frequency, micromotion, AC Stark and Zeeman shifts, etc.) – these values and their effects on atomic transitions will be discussed. The presentation will also include a comparison between simulation and experimental data of the AC Zeeman shifts for two traps designed and measured by Sandia National Labs to illustrate the simulations’ accuracy. A sample trap design will be used to demonstrate the simulation method, its results, and techniques for improving and optimizing trap design. With an accurate and reliable method for simulating ion traps, the design process for new chips can be affordably simplified.

Towards a Radium-225 ion optical clock

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Radium-225 has nuclear spin I=1/2 and additional favorable properties for quantum information science and optical clocks. Radium-225 is also sensitive to probes of fundamental symmetries due to its octupole-deformed nucleus. We report measurements of the hyperfine structure of the low-lying states in $^{225}\mathrm{Ra}^+$ (15 day half-life) made with laser-cooled and trapped ions. We use a thorium-229 (7900 year half-life) source to continuously generate radium-225 in a sealed vacuum system. We measured the hyperfine splitting of the $^2S_{1/2}$ ground state with microwave spectroscopy. We also measured the $^2P_{1/2}$ excited state hyperfine splitting and the $^2D_{3/2}$ excited state, completing the measurements of the structures needed for Doppler cooling the ion and for making a three-laser optical clock. In the near future, we are aiming to perform spectroscopy of the $D_{5/2}$ states, including the first-order magnetic field insensitive clock transition, $^2S_{1/2}(F = 0, m_F = 0) \leftrightarrow ^2 D_{5/2}(F = 2, m_F = 0)$.

Industrially microfabricated ion traps for quantum information processing

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Scaling the number of qubits in trapped ion quantum computers requires reliable fabrication of large ion traps with integrated optics and electronics. Infineon Technologies provides industrial fabrication of microfabricated ion traps with a wide tool park as well as precise process control and in-line measurement tools that allow increased trap complexity while ensuring high reliability and reproducibility. I will report on our fabrication of various ion traps on silicon as well as on dielectric substrates (fused silica, sapphire), on the development of through-silicon and through-glass vias, on the integration of optical waveguides, on the use of Kelvin probe force microscopy for DC surface potential measurements, and on the development of electronic devices that can operate at 4 K. Finally, I will present our capabilities to test and characterize ion traps. With a second-generation ion-trap socket, we achieve fast and reliable trap exchanges that enable rapid development cycles.

Toward precision spectroscopy of CHDBrI$^+$ in search of PV

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The weak force is predicted to break the parity symmetry between left and right-handed chiral molecules, but so far the effect has eluded detection. We are developing a trapped chiral molecular ion version of the search for PV. Our candidate molecule, CHDBrI$^+$ is predicted to be preparable via state-selective ionization [1] and to exhibit a large PV shift of a few Hz for the C-H bend vibrational transition, where the transition's natural linewidth is narrower than the shift [2].

We will discuss the status of the experiment including our ion trap that is integrated with a pulsed velocity map imaging detector for internal state population detection of the molecules. We will also discuss the advantages chiral molecules have in searches for new physics [4].

[1] Landau et al. *J. Chem. Phys.* **159**, 114307 (2023)
[2] Eduardus et al. *Chem. Commun.*, **59**, 14579 (2023)
[3] Erez et al. *Phys. Rev. X* **13**, 041025 (2023)
[4] Baruch et al. *arXiv:2406.02281*, (2024)

Long-lived metastable-qubit memory

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Coherent storage of quantum information is crucial to many quantum technologies. Long coherence times have been demonstrated in trapped-ion qubits typically stored in the ground states. However, recent research suggests qubits encoded in metastable states could provide architectural benefits for quantum information processing, such as the possibility of effective dual-species operation in a single-species system and erasure-error conversion for fault-tolerant quantum computing. Here we demonstrate long-lived encoding of a quantum state in the metastable states of a trapped ion. By sympathetically cooling with another ion of the same species and constantly monitoring for erasure errors, we demonstrate a coherence time of 136(42) seconds with a qubit encoded in the metastable $5D_{5/2}$ state of a single ^{137}Ba$^+$ ion.

Stabilization of cat-state manifolds in trapped ion systems outside the Lamb-Dicke regime

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Schrödinger's cat qubits are a promising candidate for bosonic error-correction and have been the subject of extensive theoretical and experimental investigation. We introduce a new paradigm [1] to stabilize cat-like states using interfering gain and loss processes with different nonlinear dependence on the energy of the oscillator. Where these competing processes are equal in strength, we show that the steady state features manifolds of multi-component cat states with various rotational symmetry, energy distributions, and degeneracy. We show that our method can be implemented in trapped ion systems, where the desired nonlinear interactions naturally emerge from the ion-light coupling outside the Lamb-Dicke regime.

[1] I. Rojkov, M. Simoni *et al.*, arXiv:2407.18087 (2024)

Scalable Multispecies Ion Transport in a Grid Based Surface-Electrode Trap

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We present and characterize a scalable method for the control of ion crystals in a grid-based surface-electrode Paul trap. By combining co-wiring of control electrodes at translationally symmetric locations in each grid site with the site-wise ability to exchange the voltages applied to two special electrodes selected by a binary input, site-dependent operations can be achieved using only a fixed number of analog voltage signals and a single digital input per site. We deploy this method, with control of this voltage exchange done in software, to perform a conditional exchange of ions between adjacent sites on the grid, realizing exchange rates of up to 2.5 kHz over a multi-site region of interest with sub-quanta motional excitation of the crystal's axial modes.

Trapped-Ion Quantum Simulation of Electron Transfer Models with Tunable Dissipation

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The properties of trapped ions make them a pristine platform for simulating the quantum dynamics of spin and spin-boson systems. In this work, we experimentally simulate a paradigmatic model of molecular electron transfer governed by the open-system dynamics with a pair of trapped $^{171}\text{Yb}^+$ and $^{172}\text{Yb}^+$ ions. We employ the hyperfine ground states of the $^{171}\text{Yb}^+$ ion to emulate the electronic degree of freedom. Using the $^2\text{S}_{1/2}$ – $^2\text{D}_{3/2}$ optical transition of the $^{172}\text{Yb}^+$ ion for sympathetic cooling, we perform bath engineering on a collective motional mode encoding a reaction coordinate that is coupled to the donor and acceptor states via coherent spin-phonon drive. By independently controlling the donor-acceptor energy difference, the electronic and vibronic couplings, and the motional relaxation rate, we observe the transfer dynamics in nonadiabatic and strongly adiabatic regimes.

Process development and microfabrication of scalable multi-level $^{171}\text{Yb}^+$ surface-electrode ion traps

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The MIQRO project develops microfabricated ion traps for scalable quantum computing utilizing microwave and static magnetic fields generated by micro magnets for quantum logic gates [1]. Future applications require integrated electrodes and additional units in ion trap substrates to enhance connectivity and optimize optical access. Assembly and connection technologies need to evolve to meet growing demands. We present microfabrication techniques for producing multi-layer [2] quantum processor chips with Through Substrate Vias (TSVs), integrating various technologies in a single process flow.

[1] F. Mintert *et al.*, Phys. Rev. Lett. 87, **257904** (2001)

[2] A. Bautista-Salvador *et al.*, New Journal of Physics 21, **043011** (2019)

Quantum Simulation of Spin-Boson Models with Structured Bath

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The spin-boson model is a widely used representation of open quantum systems. Trapped ions present a natural platform for simulating the quantum dynamics of such models, thanks to the presence of both high quality internal qubit states and the motional modes of the ions that can simulate the relevant quantum degrees of freedom. In our work, we extend the previous body of work that focused on coherent coupling of the spins and bosons to perform quantum simulations with structured dissipative baths using the motional states of trapped ions. We demonstrate the capability for adjusting the bath's temperature and continuous spectral density by adding randomness to fully programmable control parameters. The experimental outcomes closely align with theoretical predictions, indicating successful simulation of open quantum systems using a trapped-ion system. [1].

[1] K. Sun *et al.*, arXiv:2405.14624 (2024)

Quantum Logic Spectroscopy with Polyatomic Molecules

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Over the last decade, the quantum logic spectroscopy[1] (QLS) community has expanded its aspiration from confining the atoms to molecules into the ion traps. The ability to perform precision measurements with polyatomic molecules would introduce brand-new experiment opportunities, as these molecules serve as sensitive sensors for fundamental physics[2, 3]. In this work, we present collective theoretical efforts to address the challenge posed by the densely populated ro-vibrational levels in polyatomic molecules. Specifically, we will discuss the design of a single state preparation scheme and the resolution of hyperfine structure, employing interdisciplinary approaches that integrate artificial intelligence, AMO physics, and quantum chemistry.

[1] P. O. Schmidt, T. Rosenband, C. Langer, W. M. Itano, J. C. Bergquist, and D. J. Wineland, Science **309**, 749 (2005).

[2] M. Kozlov and S. Levshakov, The Astrophysical Journal **726**, 65 (2010).

[3] V. Letokhov, Physics Letters A **53**, 275 (1975).

Eliminating Qubit-Type Cross-Talk in the *omg* Protocol

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The omg protocol is a promising paradigm that uses multiple, application-specific, qubit subspaces within the Hilbert space of each single atom during quantum information processing. A key assumption for omg operation is that a subspace can be accessed independently without deleterious effects on informa- tion stored in other subspaces. We find that intensity noise during laser-based quantum gates in one subspace can cause decoherence in other subspaces, po- tentially complicating omg operation. We show, however, that a magnetic-field- induced vector light shift can be used to eliminate this source of decoherence. As this technique simply requires choosing a specific, magnetic field-dependent po- larization for the gate lasers, it is straightforward to implement and potentially helpful for omg-based quantum technology.

[1] S. R. Vizvary *et al.*, Phys. Rev. Lett. 132, 263201 (2024).

Efficient Autoionization and Ion Trap Loading of ^{133}Ba^{+}

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The ^{133}Ba^{+} trapped ion qubit provides many advantageous qualities for trapped ion quantum technology, including nuclear spin $I = 1/2$, visible wavelength cooling transitions, and a long lived ($\tau = 30s$) metastable $D_{5/2}$ state. This also makes it the ideal candidate to implement the omg (optical-metastable-ground) architecture that utilizes three qubits in a single atom. However due to its low abundance, scaling technology utilizing this ion requires highly efficient photoionization. We present advances in the photoionization and loading of barium trapped ions. We will highlight a novel scheme for two step photoionization through the $5d6p^3D_1$ level to multiple autoionizing states. This resonant photoionization technique allows for isotope selective ionization of low abundance barium isotopes.

A cryogenic optical cavity for trapped Yb^+ quantum networking

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Interfacing matter-based quantum processors with flying qubits is the mainstream path to future quantum networks. The combination of trapped ions and telecom-wavelength photons shows promise for quantum networking on long baselines (> 10 km). A recent proposal [1] suggests using $^{171}\mathrm{Yb}^+$ with an optical cavity to enhance single-photon emission at 1650 nm.

We demonstrate a high-finesse Fabry-Perot cavity in a closed-cycle 4K flow cryostat, integrated with a blade Paul trap. The cryogenic environment permits rapid prototyping of ion-cavity structures in vacuum, though mechanical stability is challenged by cryocooler vibrations. Stability is achieved with improved cryostat design, a monolithic fiber-coupled cavity mirror, and active stabilization. Additionally, a meta-material lens couples the TEM00 cavity mode into a fiber, potentially reaching over 90% efficiency. Such compact cavity-metalens-fiber integration is less susceptible to cryocooler vibrations.

[1] W. Wang *et al.*, in OSA Quantum 2.0 Conference QW6A.12 (2020)

Scalable, high-fidelity all-electronic control of trapped-ion qubits

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The central challenge of quantum computing is performing high-fidelity quantum gates at scale. We present a vision for an electronically controlled trapped-ion quantum computer that alleviates this bottleneck by utilizing shared current-carrying traces and local tuning electrodes in a microfabricated chip. We deomnstrate scalable, site-selective single- and two-qubit gates in an ion trap that can control up to 10 qubits. Electronic single-qubit gates perform at 99.99916(7)% fidelity, with consistent, low crosstalk across the device. We also electronically generate two-qubit maximally entangled states with 99.97(1)% fidelity and long-term stable performance over continuous system operation. These state-of-the-art results validate the path to large quantum computers based on electronically controlled trapped-ions.

Photodissociation spectra of CaOH$^+$: towards single trapped polyatomic ion spectroscopy

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Generated by the chemical reaction between trapped Ca$^+$ ions and background water molecules, CaOH$^+$ can serve as a test-bed for extending the current research on trapped diatomic molecular ions to polyatomic species. We here present our measurement of the photodissociation spectra of single trapped CaOH$^+$ based on our new experimental platform[1]. With this setup, we plan to further investigate the rovibronic degrees of freedom of CaOH+ with entanglement-enhanced ultrafast spectroscopy[2] and quantum logic spectroscopy methods[3].

[1] Z. Wu *et al.*, J. Chem. Phys. 161, **044304** (2024)

[2] P. Schindler, New J. Phys. 21, **083025** (2019)

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

Temporal multiplexing for remote ion-photon quantum interface

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We implement a temporally multiplexed single-photon quantum interface through the coherent transport of a chain of nine calcium ions over 74 μm within 94 μs, with synchronized single ion excitation [1]. We confirm the nonclassical nature of these multiplexed, on-demand photons through Hanbury-Brown-Twiss experiments, yielding a $g_2(0)$ value of 0.060(13). Together with our supplementary measurements, we determine that the crosstalk between the multiplexed modes is mainly limited by the intensity crosstalk of the addressing beam for photon excitation. Additionally, we characterize the motional heating after transport and find that it is coherently excited to as much as $\bar{n} \approx 110$ for the center-of-mass mode, dominated by that the transport speed close to motional frequency.

[1] B. You *et al.*, arXiv preprint arXiv:2405.10501 (2024)

Towards precision spectroscopy of polyatomic molecular ions

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The complex degrees of freedom of polyatomic molecules make them a promising platform for precision measurements to search for new physics beyond the Standard Model. For example, the inversion transition spectrum of H_3O^+ can be used to probe spatial or temporal variations of the electron-to-proton mass ratio predicted by unification theories [1]. In this experiment, we aim to co-trap a single molecular ion with an atomic ion to study molecular transitions with enhanced quantum state control and spectroscopic precision using quantum logic spectroscopy (QLS)-based protocols. Here, we present calculations of the hyperfine structure of H_3O^+ and the experimental design of our vacuum and cryogenic systems.

[1] M. G. Kozlov and S. A. Levshakov (2011)

3D-Printed Micro Ion Trap for Quantum Information Processing

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We demonstrate miniaturized 3D-Paul traps fabricated using high-resolution 3D printing technology. Using two-photon polymerization provides a route to expand the geometric design-freedom of ion traps and fulfill the trap efficiency and scalability requirements for applications including QIP. With such a 3D-printed trap, we confine single calcium ions nearly throughout the full stability region. The tight confinement eases the ion cooling requirements and allows us to demonstrate high-fidelity coherent operations on a single optical qubit after Doppler cooling only. In addition, we characterize the heating rates and further demonstrate Mølmer–Sørensen entangling operations between two trapped calcium ions confined in such a trap [1].

[1] S. Xu *et al.*, arXiv: 2310.00595 (2023)

Experimental observation of symmetry-protected signatures of N-body interactions.

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Identifying and understanding higher-order interactions in quantum systems with unknown Hamiltonians is challenging. Recent research reveals that under a U(1) symmetry, which conserves charge or number, N-body interactions show a unique N-body phase, distinct from fewer-body interactions [1]. This study explores the time evolution of quantum systems governed by U(1)-invariant Hamiltonians. We develop and demonstrate an efficient method to detect N-body interactions, even in the presence of unknown two-body interactions. This research has been supported by the IARPA LogiQ program, NSF STAQ program, DOE program on Quantum Computing in Chemical and Material Sciences, AFOSR MURI on Quantum Measurement and Verification, and AFOSR MURI on Interactive Quantum Computation and Communication Protocols.

[1] I. Marvian, Nature Physics 18 (3), 283-289, (2022)