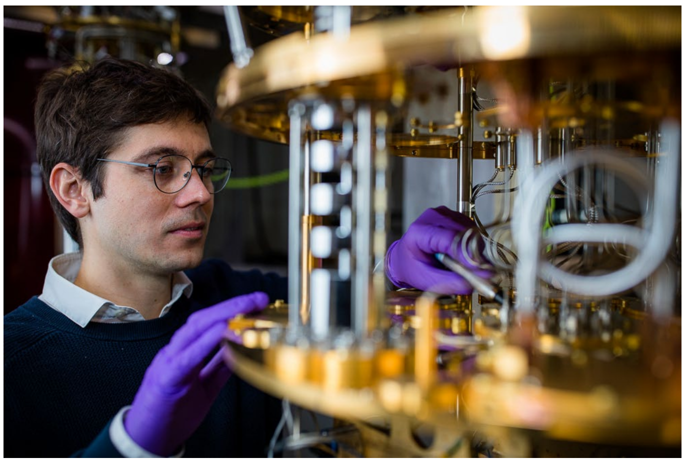

2021

RESEARCH HIGHLIGHTS

MIT Center for Quantum Engineering

Selected research highlights from members of the Center for Quantum Engineering

Foreword

The MIT Center for Quantum Engineering (CQE) aims to foster a quantum ecosystem of interdisciplinary research and education at MIT as well as strong industry relationships in quantum science and technology.

"Quantum Engineering" encompasses both science and engineering disciplines. The range of MIT research activities in these areas is broad, spanning fundamental and applied research in quantum sensing, quantum networking and communication, and quantum computing.

Here, we highlight quantum research from our CQE membership across the School of Engineering, School of Science, and MIT Lincoln Laboratory. The research here represents a sampling of the research being performed by our 60+ CQE members and their research groups, including post docs, graduate students, and undergraduate researchers.

This is our first annual MIT-CQE Research Highlights. Please enjoy this sampling of the fantastic research being performed at MIT in quantum science and engineering.

William D. Oliver

Director, MIT Center for Quantum Engineering (CQE)

Professor of Electrical Engineering and Computer Science and of Physics
Lincoln Laboratory Fellow

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MIT-CQE Members

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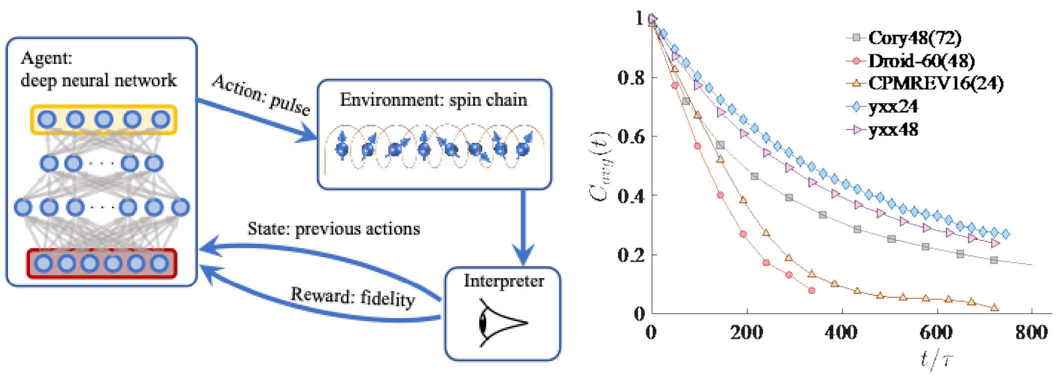
A programmable quantum simulator with nuclear spins

P. Peng, A. Stasiuk, P. Cappellaro
Sponsorship: [NSF, Mathworks fellowship], Doc Bedard fellowship (A.S.)

Nuclear spins in solids provide an intriguing platform to study quantum many-body dynamics and its reduction to emergent hydrodynamics. Their use has so far been limited due to the lack of individual spin addressing that reduces the types of observables one can measure and the Hamiltonian that can be simulated.
We have recently developed novel control techniques to engineer a broad range of Hamiltonian with a precision that allows long evolution times.

First, we used reinforcement learning to find efficient pulsed control sequences that engineer Floquet (time-periodic) Hamiltonians. The interactions over a period achieves a desired Hamiltonian (such as, the no-operation Hamiltonian). We found that using reinforcement learning can achieve better performance than intuition-based control sequences that have been used for decades, as well as more recent ones that are based on analytical formulas.

Second, we are combining control of the Hamiltonian and of its interaction with the environment to extend the reach of Hamiltonian engineering. In particular, we are interested in engineering interactions that can be tuned from non-interacting models, to integrable interacting models, and to non-integrable models, while also tuning the strength of disorder. Thanks to this toolset, we can investigate the dynamics of spin and energy (their transport) in variable conditions and observe the transition from ballistic to diffusive, to localized regimes. Given the large system size, our programmable quantum simulator based on nuclear spins provides a powerful platform to investigate (generalized) hydrodynamics, localization and ergodicity.



Left: High-level RL protocol for Hamiltonian engineering. The agent, realized as a deep neural network, takes an action based on the current state. This action applies the corresponding control operation to the spin chain. The interpreter updates the state based on the chosen action, and feeds it to the agent to take next action. When the final time is reached, the interpreter calculates the reward, which is then used to optimize the agent.
Right: comparison of the performance of selected sequences (Cory48, CPMrev16, Droid60) and of our newly introduced sequences (yxx24 and yxx48), found with reinforcement learning. We measure the average survival probability of the collective polarization around the 3 axes (x,y,z), C_{avg}, as a function of the normalized time (for a time period of τ=6μs).

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arXiv:2102.13161 (2021)
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Nat. Phys., s41567 (2021)

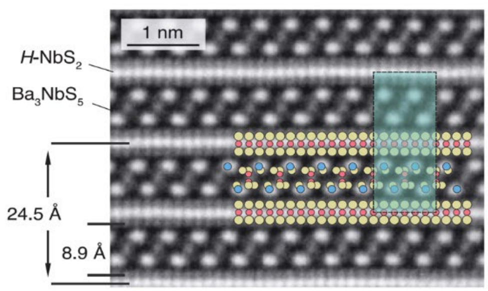
The intersection of fundamental solid state physics, solid state chemistry, and nanoscience

Joseph Checkelsky, Dept of Physics, New Quantum Materials, checkelsky.mit.edu

Research in Checkelsky lab focuses on the study of exotic electronic states of matter through the synthesis, measurement, and control of solid state materials. Of particular interest are studies of correlated behavior in topologically non-trivial materials, the role of geometrical phases in electronic systems, and novel types of geometric frustration. These studies aim to uncover new physical phenomena that expand the boundaries of understanding of quantum mechanical condensed matter systems and also to open doorways to new technologies by realizing emergent electronic and magnetic functionalities. The group is excited to pursue new directions at the cross section of quantum information and quantum materials.

The experimental approach of the laboratory is to work at the intersection of fundamental solid state physics, solid state chemistry, and nanoscience. Techniques range from transport and thermodynamic measurements to bulk single crystal and epitaxial thin film growth to nanoscale probe and device fabrication. We aim to generate an active feedback between these methodologies to incisively probe the fundamental physics of interest.

We have recently synthesized a new type of naturally layered quantum materials (*1*) (figure below left) that may potentially support a modulated superconducting state (*2*) (figure below right) relevant for quantum computing.



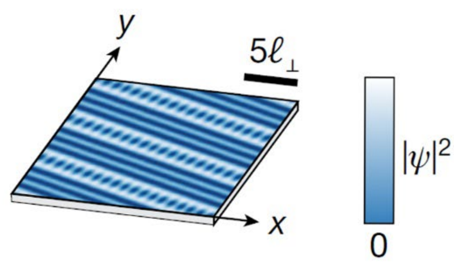


Figure 1 – (Left) Cross sectional TEM view of new quantum material $Ba_6Nb_{11}S_{28}$. (Right) Numerical simulation of modulated superconducting state.

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2. A. Devarakonda, T. Suzuki, S. Fang, J. Zhu, D. Graf, M. Kriener, L. Fu, E. Kaxiras, J. G. Checkelsky, Signatures of bosonic Landau levels in a finite-momentum superconductor. *Nature*. **599**, 51–56 (2021).

Photonic integration for trapped-ion quantum information science

F.W. Knollmann, B. Hanly, B. Hasbach, T. McCourt, R. Morgan, S.L. Todaro, A. Ungar, D. Voronin, C.D. Bruzewicz, P.T. Callahan, D. Kharas, M. Kim, R. Maxson, R. McConnell, A. Medeiros, D. Reens, C. Sorace-Agaskar, R. Swint, J. Notaros, I.L. Chuang, J. Chiaverini
Sponsorship: NSF QLCI Q-SEnSE, NSF QLCI HQAN

A major architecture for large-scale quantum computing with trapped ions relies on individual computational nodes that are linked via quantum entanglement established using photons. This multi-node architecture would also benefit hybrid networks between trapped ions and other quantum systems. Achieving quantum computing nodes and quantum networks of practical scales will require modularization of the quantum control hardware and reduction of the equipment and alignment overhead.

To realize this vision, we are developing new methods of integrating light delivery and collection into photonic waveguides on chip. Using a complete visible-light integrated photonics platform developed at Lincoln Laboratory, we can realize these novel optical elements in chip-scale ion traps. To achieve qubit array addressing without free-space optics, we are integrating emission structures for light delivery at colors and polarizations necessary for trapped-ion laser cooling and qubit manipulation. Using these elements in reverse, i.e. by collecting emitted single photons into waveguides and combining them on a beam splitter, ion qubits can be remotely entangled via heralded photon coincidence using solely integrated optical elements. This entanglement between nodes would allow many chains of trapped ions, functioning as small quantum computers, to be coherently interconnected via teleported logic operations. Moreover, multiplexing of trapped-ion modules will allow for higher-speed entanglement of spatially separated nodes or chains; chip-integrated collection optics can provide the registrations and repeatability needed for such multiplexed protocols. Through such ion-qubit-control integration, micro- and nano-fabricated photonic elements can pave the way toward high-performance distributed quantum computing and quantum networking with trapped ions.
* We wish to acknowledge generous support from NSF through the Q-SEnSE and HQAN Quantum Leap Challenge Institutes, Awards # 2016244 and # 2016136.

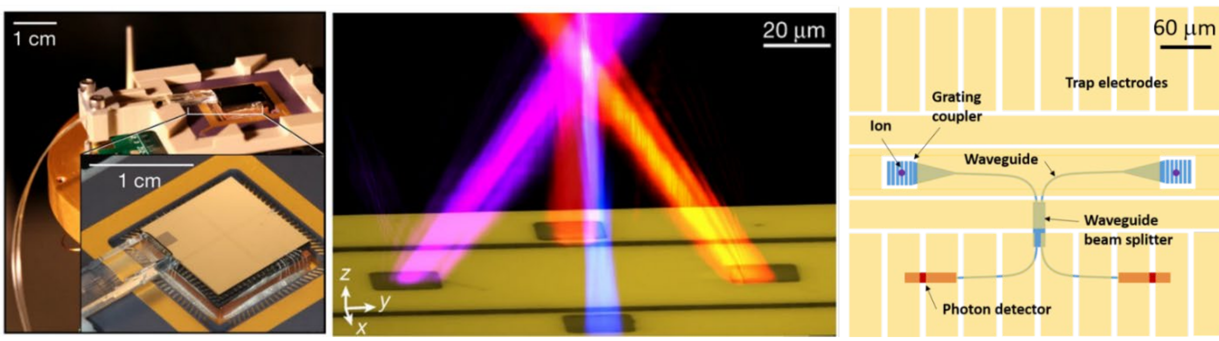

Figure: Integrated optic light delivery and collection. LEFT: Fiber-array coupling of light between fibers and trap-chip waveguides. The inset shows a detail view of a trap chip with waveguides leading to grating couplers near the ion trapping location in the center (chip fabricated and packaged at MIT Lincoln Laboratory). CENTER: Measured beam profiles of light at multiple wavelengths emitted from four grating couplers for excitation of an ion trapped nominally near their intersection above the chip. These wavelengths (false color) are used for cooling and manipulation of Sr^+ ion qubits. RIGHT: Concept for on-chip photon-mediated ion entanglement (top view). Light is collected from ions trapped above grating couplers; photons are routed via waveguides to photonic beam splitters that erase "which-path" information, and photon coincidences may be registered via single-photon detectors on-chip (as shown here) or off chip. All elements may be integrated below trap electrodes (shown here as partially transparent for clarity).

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Trapped-Ion Quantum Information Processing using Metastable Qubits

S.L. Todaro, K. DeBry, X. Shi, S. B. Alterman, F.W. Knollmann, G. Mintzer, T. McCourt, J. Sinanan-Singh, J. Stuart, C.D. Bruzewicz, J. Chiaverini, I.L. Chuang
Sponsorship: ARO

Most quantum information encodings in trapped ions use two levels to form a qubit, defined either between two Zeeman or hyperfine sublevels of the ground electronic state or between the ground state and a long-lived metastable state. A third category is the metastable qubit, in which quantum information is encoded in sublevels of the metastable state. Qubits in this manifold would be largely insensitive to scattered laser light addressing a neighboring qubit in the ground state manifold, potentially enabling dual-species-like resilience from error in a chain of identical ions, leading to more straightforward ion-array trapping and manipulation.

Barium-133 ions have accessible visible and infrared transition wavelengths, hyperfine sublevels, and a metastable state with a 26 second lifetime, making them appealing for this application. However, this isotope is radioactive, with a 10.5-year half-life. We are characterizing the production of neutral and ionic barium by laser ablation, which could enable isotope-selective loading of barium ions into chip-based ion traps from a small radioactive source. We are determining, via numerical calculation, required intensities and laser frequency detunings for high-fidelity quantum logic using Raman excitation of either the ground states or metastable states of this isotope in order to guide future quantum-computing architecture explorations.

We are also performing preliminary experimental investigations of a metastable qubit encoded in Zeeman sublevels of the $D_{5/2}$ state of calcium-40 ions (which have a less favorable electronic structure but can be readily trapped) using a combination of lasers and RF fields. Imposing a light-shift via a quadrupole transition, we can isolate two sublevels of the D manifold to explore basic metastable-qubit primitives in single and multi-ion crystals. This new level of quantum control will allow us to efficiently realize quantum algorithms, including quantum signal processing, using the expanded Hilbert space provided by the metastable states.
* This work was supported in part by the US Army Research Office under award W911NF-20-1-0037. SLT acknowledges support from the Intelligence Community Post-Doctoral Fellowship. KD acknowledges support from the Doc Bedard Fellowship and the Laboratory for Physical Sciences

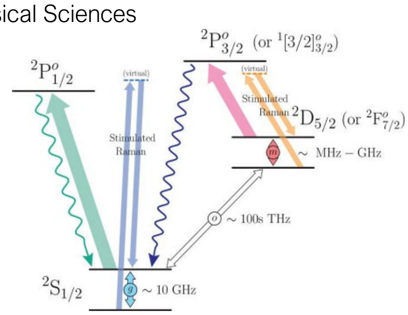

Figure: Level structure of trapped ions housing multiple qubit types. Ground state ("g"), optical ("o"), and metastable ("m") qubits are all potentially addressable in ion species being explored in this project (e.g. Ba^+, Ca^+). Fields used to perform operations on "m" qubits will not affect quantum information stored in nearby "g" qubits (or vice versa), and "o" qubits can be used for high-fidelity state preparation and readout, allowing for great flexibility in registers of a single ion species.

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Efficient classical simulation of random shallow 2D quantum circuits

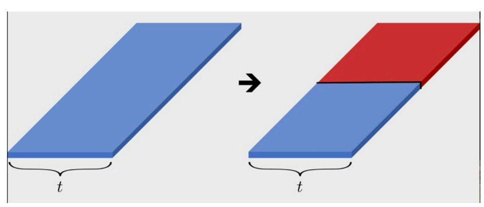
J. Napp, R. L. La Placa, A. M. Dalzell, F. G. S. L. Brandao, A. W. Harrow
Sponsorship: NSF, DOE, IBM

A central question of quantum computing is determining the source of the advantage of quantum computation over classical computation. Even though simulating quantum dynamics on a classical computer is thought to require exponential overhead in the worst case, efficient simulations are known to exist in several special cases. It was widely assumed that these easy-to-simulate cases as well as any yet-undiscovered ones could be avoided by choosing a quantum circuit at random. We prove that this intuition is false by showing that certain families of constant-depth, 2D random circuits can be approximately simulated on a classical computer in time only linear in the number of qubits and gates, even though the same families are capable of universal quantum computation and are hard to exactly simulate in the worst case (under standard hardness assumptions). While our proof applies to specific random circuit families, we demonstrate numerically that typical instances of more general families of sufficiently shallow constant-depth 2D random circuits are also efficiently simulable.

We propose two classical simulation algorithms. One is based on first simulating spatially local regions which are then ``stitched" together via recovery maps. The other reduces the 2D simulation problem to a problem of simulating a form of 1D dynamics consisting of alternating rounds of random local unitaries and weak measurements. Similar processes have recently been the subject of an intensive research focus, which has observed that the dynamics generally undergo a phase transition from a low-entanglement (and efficient-to-simulate) regime to a high-entanglement (and inefficient-to-simulate) regime as measurement strength is varied. Via a mapping from random quantum circuits to classical statistical mechanical models, we give analytical evidence that a similar computational phase transition occurs for both of our algorithms as parameters of the circuit architecture like the local Hilbert space dimension and circuit depth are varied, and additionally that the effective 1D dynamics corresponding to sufficiently shallow random quantum circuits falls within the efficient-to-simulate regime.

Implementing the latter algorithm for the depth-3 "brickwork" architecture, for which exact simulation is hard, we found that a laptop could simulate typical instances on a 400x400 grid with total variation distance error less than 0.01 in approximately one minute per sample, a task intractable for previously known circuit simulation algorithms. Numerical results support our analytic evidence that the algorithm is asymptotically efficient.

(a)



(b)

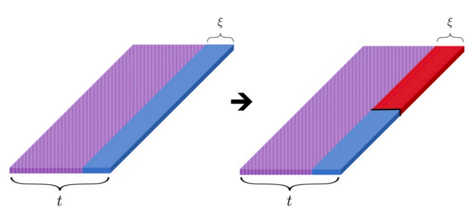
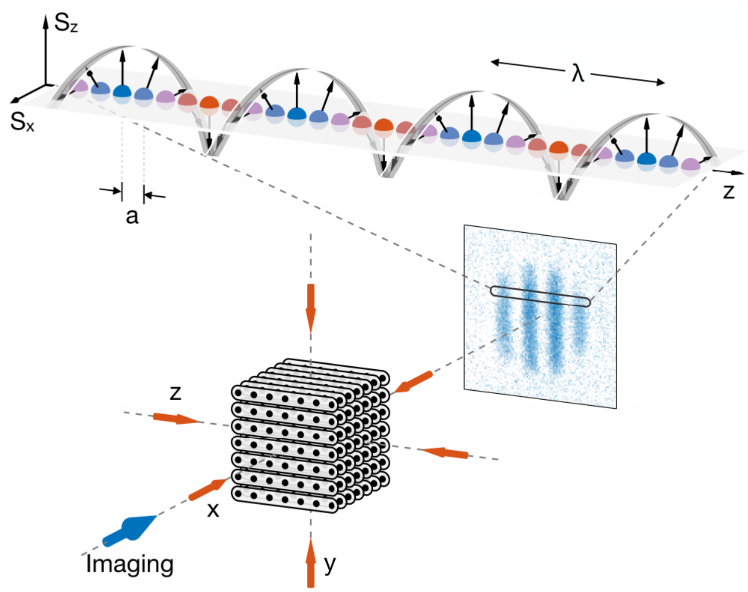


Fig caption: A random quantum circuit is mapped to a stat mech model. The ordered phase of the stat mech model (a) corresponds to high entanglement and the simulation algorithm failing; the disordered phase (b) corresponds to low entanglement and the simulation algorithm succeeding.

Spin dynamics for anisotropic Heisenberg models

Wolfgang Ketterle, Atomic Quantum Gases
Sponsorship: NSF, DoD

Simple models of interacting spins play an important role in physics. They capture the properties of many magnetic materials, but also extend to other systems, such as bosons and fermions in a lattice, systems with gauge fields, high-Tc superconductors, and systems with exotic particles such as anyons and Majorana fermions. In order to study and compare these models, a versatile spin quantum simulator is needed. Realizing such a system has been a long-standing goal in the field of ultracold atoms. So far, spin transport has only been studied in the isotropic Heisenberg model. Here we implement the Heisenberg XXZ model with adjustable anisotropy and use this system to study spin transport and spin dynamics far from equilibrium after quantum quenches from imprinted spin helix patterns (see figure).



Creation of a spin helix state, realized from two hyperfine states (spin |↑) and |↓)). The spin S winds within the Sz Sx-plane as a function of position z in the spin chain. Deep optical lattices along x and y create an array of independent spin chains. The z-lattice is shallower and controls spin transport along each chain.

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Catching Bethe phantoms and quantum many-body scars: Long-lived spin-helix states in Heisenberg magnets.
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Phys. Rev. X **11**, 041054 (2021), https://doi.org/10.1103/PhysRevX.11.041054

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Spin transport in a tunable Heisenberg model realized with ultracold atoms.
Nature **588**, 403–407 (2020), https://doi.org/10.1038/s41586-020-3033-y

Nonreciprocal Magnons for directional signal transmission

J. Han, Y. Fan, B. C. McGoldrick, J. Finley, J. T. Hou, P. Zhang, Z. Hu, and L. Liu
Sponsorship: AFOSR, NSF

One of the important applications of magnetic materials in information processing and communication is to provide the function of nonreciprocity. Driven by the need for high performance, compact nonreciprocal devices, new mechanisms that can provide passive, directional isolation of signals are being pursued at the submicrometer scale, among which spin waves show unique potentials due to the tunability and the possibility for on-chip integration. In previous studies, nonreciprocal spin waves have been achieved through the magnetostatic surface mode or by asymmetrically modifying the spin wave dispersion under the effect of the Dzyaloshinskii−Moriya interaction. Most recently, the dipolar coupling between different magnetic layers has been studied for nonreciprocity, where the dispersion relation is shifted asymmetrically or the spin wave mode is excited directionally. However, these nonreciprocal effects are limited to coherent spin waves under single frequencies in the ballistic regime. It remains elusive whether the nonreciprocity can be reached for incoherent, diffusive magnons that occupy a broadband spectrum.

In this work, through nonlocal, spin mediated charge-transfer measurements, we find that in a bilayer composed of a ferrimagnetic insulator $Y_3Fe_5O_{12}$ (YIG) and a magnetic alloy NiFe, the diffusion of the spin Hall effect-induced incoherent magnons has unequal transmission coefficients along opposite directions. We further verify that the sign of nonreciprocity is switchable by magnetic fields through the control of the bilayer's magnetic orientation, and the magnon diffusion length is asymmetric over the transmission direction. This nonreciprocal magnon diffusion can be explained by the asymmetric magnon attenuation rate induced by the interlayer dipolar coupling. We believe this work provides an efficient mechanism for designing passive devices with directional signal isolation that works in the diffusive regime. For future applications, devices with electrically programmable directional signal isolation can also be achieved by integrating our device with voltage- or current-induced switching of the magnetic gate.

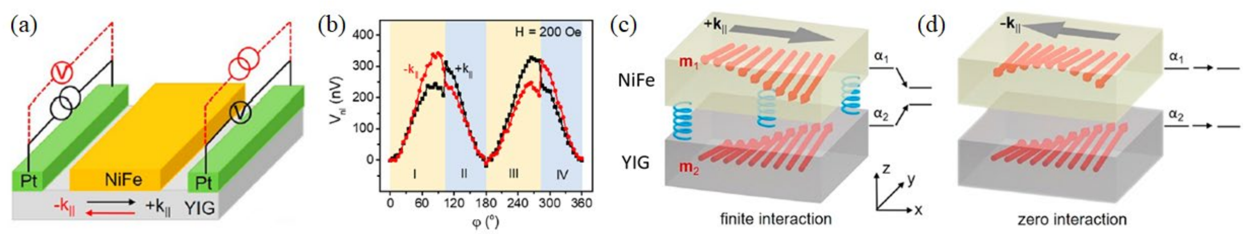

Figure 1. (a) Schematic of a nonlocal device consisting of a YIG layer with two Pt electrodes and a NiFe strip on top. When using the left Pt electrode as the spin injector and using the right one as the detector (black, solid lines), magnons propagate from left to right with $+k_{\|}$ momentum, vice versa (red, dotted lines). (b) The non-local voltage has different angular dependence $V_{nl}(\varphi)$ for $+k_{\|}$ and $-k_{\|}$ magnons. (c) For the right-going ($+k_{\|}$) magnon, the two layers are coupled through dynamic dipolar interactions, resulting in a modulation of damping coefficients, i.e., α_1 decreases and α_2 increases. (d) For the left-going ($-k_{\|}$) magnon, the dynamic dipolar field from the magnetic oscillation does not induce interlayer dipolar coupling. The damping factors of the two layers remain unchanged.

Integrated Grating Coupler Design for Advanced Cooling of Trapped Ions

A. Hattori, S. Corsetti, T. Sneh, M. Notaros, R. Swint, J. Chiaverini, J. Notaros
Sponsorship: NSF QLCI–HQAN (2016136) and MIT Center for Quantum Engineering (H98230-19-C-0292)

Integrated-photonics technology offers a scalable route towards practical quantum computing and sensing with trapped ions. Dielectric waveguides and grating couplers integrated with a surface-electrode ion-trap chip can greatly reduce the number of free-space optical components needed for laser control of many ions, overcoming a major barrier for scaling these systems.

In prior work, silicon-nitride-based grating couplers operating at visible wavelengths have been used for on-chip qubit preparation of Sr+ ions. However, since these prior devices were designed for transverse-electric emission, they have been limited to state preparation using Doppler and resolved side-band cooling.

In this work, we explore how grating couplers emitting different polarizations of light, including transverse-magnetic and circular, can be integrated into a surface-electrode ion-trap chip for more efficient qubit state preparation through advanced cooling modalities. Specifically, we investigate how these polarizations can be used to achieve electromagnetically-induced-transparency cooling and Sisyphus cooling, to enable higher fidelity qubit preparation with many ions in a single chip-based trap.

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[2] J. Notaros, F. Pavanello, M. T. Wade, C. M. Gentry, A. Atabaki, L. Alloatti, R. J. Ram, and M. A. Popovic, "Ultra-Efficient CMOS Fiber-to-Chip Grating Couplers," in *Proc. of Optical Fiber Communication Conference (OFC)* (OSA, 2016), paper M2I.5.

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Architectural Analysis of Quantum Algorithms for NISQ Hardware

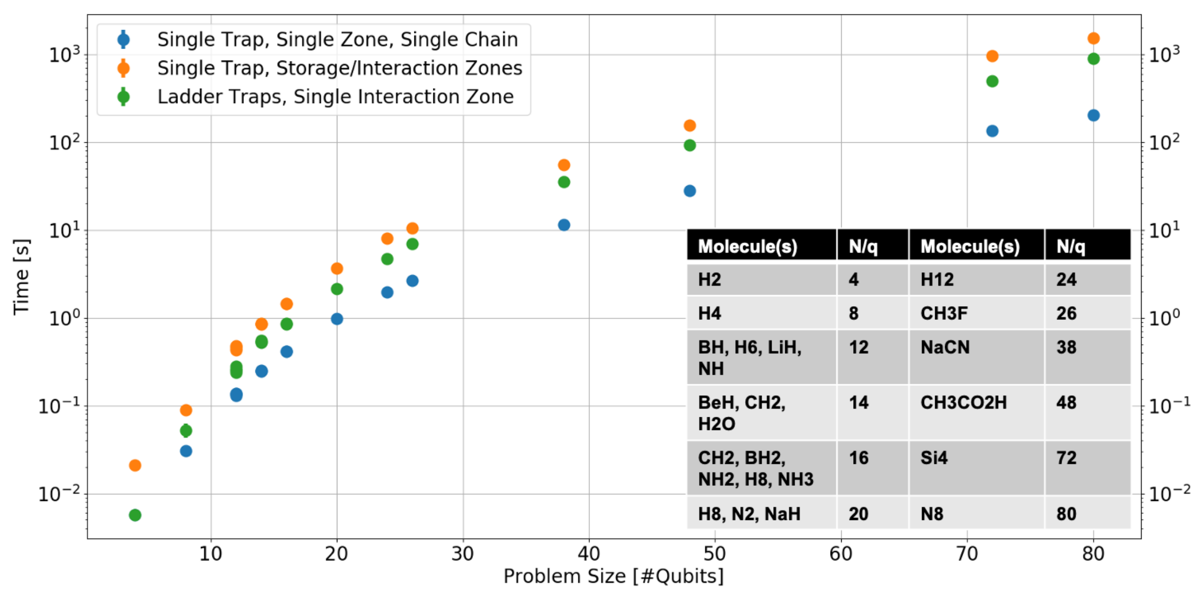
A. Kurlej, S.B. Alterman, K.M. Obenland
Sponsorship: MIT Lincoln Laboratory Technology Office

Emerging quantum computing architectures are at the cusp of showing relevance for real-world problems. The goal of our project is to investigate the architectural trade-offs that naturally occur in the design of emerging quantum computing hardware. We study these architectures using quantum benchmarks that are implementations of quantum algorithms with practical impact. At the core of our project is a quantum architecture simulation tool that will allow us to assess the impact that architecture design choices have on the resources and fidelity of the designs.

One application that we have studied extensively is quantum chemistry using the Variational Quantum Eigensolver (VQE) algorithm. We use Google's OpenFermion tool to develop chemical models and produce circuits for VQE where the goal is to find the ground state of a chemical Hamiltonian. We have studied small molecules (H2 requiring 4 qubits) as well as larger molecules like N8 (80 qubits).

We have used our framework to study three different trapped ion architectures. The results of our analysis is shown in Figure 1. The architectures used in the study are described below:

1. Single trap, single zone with one fully connected chain. This design is based on IonQ's platforms and consists of a single linear chain of ions. Operations can be performed between arbitrary qubits in the chain.
2. Single trap, multi storage and interaction zones. Ions are trapped in a linear chain, and segmented into independent zones. Interaction zones are used for logic gates, and storage zones hold idle qubits.
3. Ladder traps. This design consists of a number of isolated linear traps that are interconnected on each side via shuttling channels. The traps are able to perform independent operations in parallel.



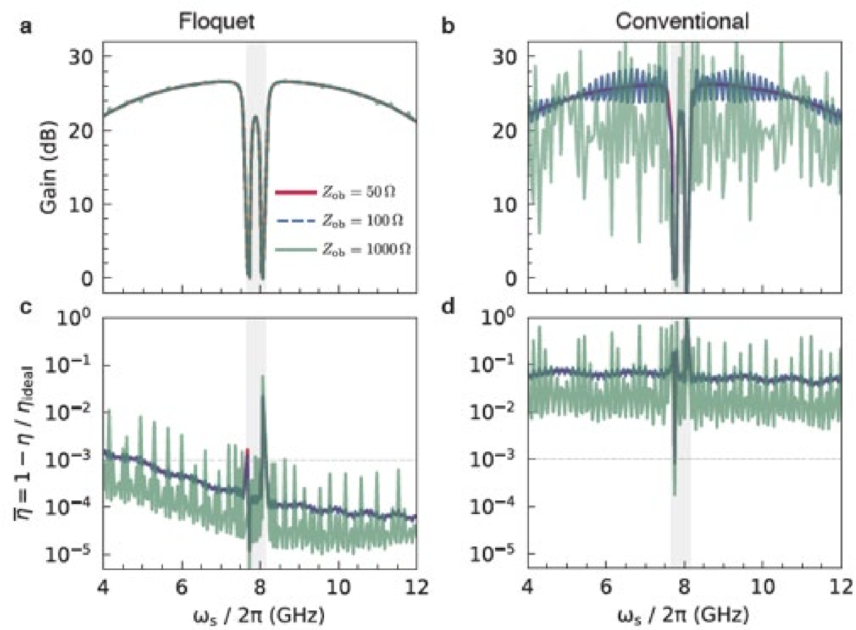
Molecule(s)	N/q	Molecule(s)	N/q
H2	4	H12	24
H4	8	CH3F	26
BH, H6, LiH, NH	12	NaCN	38
BeH, CH2, H2O	14	CH3CO2H	48
CH2, BH2, NH2, H8, NH3	16	Si4	72
H8, N2, NaH	20	N8	80

Figure 1: Total runtime for each of the three candidate architectures. We take as benchmarks VQE circuits for molecules ranging in size from 4 to 80 orbitals (qubits).

Floquet Mode Traveling Wave Parametric Amplifier

K. Peng, M. Naghiloo, J. Wang, Y. Qiu, Y. Ye, K. Serniak, A. J. Melville, W. Woods, D. K. Kim, B. Niedzielski, J. L. Yoder, M. E. Schwartz, W. D. Oliver, K. P. O'Brien
Sponsorship: AWS Center for Quantum Computing, MIT RSC from the NEC Corporation Fund for Research in Computers and Communications, and IARPA under Air Force Contract (FA8702-15-D-0001)

Floquet Mode Traveling Wave Parametric Amplifiers (Floquet TWPAs) [1] are a recently proposed new amplifier paradigm that have been theoretically predicted to overcome the bandwidth-quantum efficiency trade-off of the current state-of-the-art broadband amplifiers and are in principle broadband, quantum-limited, and crucially directional at the same time. Consequently, Floquet TWPAs can be potentially integrated with sensitive quantum systems without isolators, enabling ideal broadband quantum measurements and opening up new possibilities for various information-critical applications in quantum information processing, metrology, and astronomy. In this work, we discuss the practical advantages and challenges in realizing Floquet TWPAs on the superconducting quantum circuit platform for fast, high-fidelity qubit readout and report our experimental progress of Floquet Josephson TWPAs using a qubit-compatible aluminum fabrication process.



Performance of a Floquet TWPA and the corresponding conventional TWPA under different out-of-band impedance Z_{ob} = 50 Ohms (red), 100 Ohms (blue), and 1000 Ohms (green) respectively. The impedance environment is set to be Z=50 Ohms for frequencies below 16 GHz and Z_{ob} otherwise. (a), (b) Gain spectrum of the Floquet TWPA and Conventional TWPA respectively. (c), (d) The quantum inefficiency (smaller is better) of the Floquet TWPA and the conventional TWPA respectively.

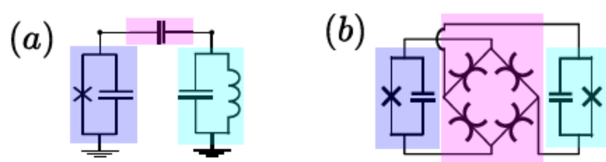
FURTHER READING

[1] K. Peng, M. Naghiloo, J. Wang, G. D. Cunningham, Y. Ye, and K. P. O'Brien, "Near-ideal quantum efficiency with a Floquet mode traveling wave parametric amplifier, arXiv:2104.08269 (2021).

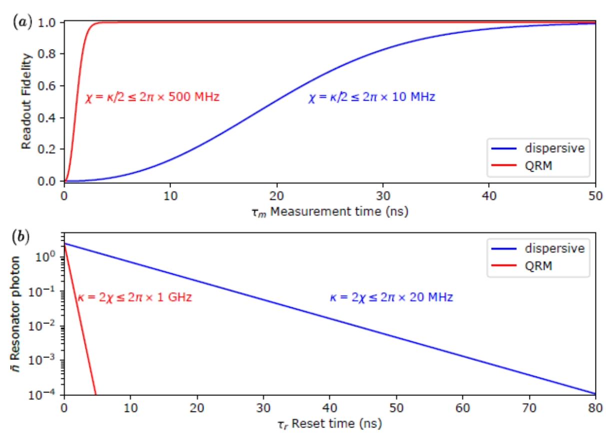
Ultrafast superconducting qubit readout and gates with a quarton coupler

Y. Ye, M. Naghiloo, K. Peng, G. Cunningham, K.P. O'Brien
Sponsorship: NSERC, MIT Center for Quantum Engineering, Laboratory for Physical Sciences (H98230-19-C-0292)

Faster entangling operations in the form of readout and two-qubit gates for superconducting qubits are essential for achieving the next milestones such as scalable quantum error correction. Entangling gate speed is directly proportional to the interaction energy, thus for CZ gates and operations involving photons including readout and bosonic code control, gate times are limited by the typically perturbatively weak nonlinear cross-Kerr or ZZ coupling energy. Here, we propose and present experimental progress towards ultrafast (order 1 nanosecond) entangling gates by using a new tunable quarton coupler capable of ultrastrong (order 1 GHz) cross-Kerr coupling [1]. The quarton coupler is compatible with existing transmon architectures and can facilitate resonator-resonator, resonator-qubit, or qubit-qubit cross-Kerr coupling for a wide range of applications including ultrafast transmon qubit readout, CZ gates, bosonic code control, and single microwave photon detection.



Lumped element readout circuit of a) state-of-art dispersive coupling; b) proposed quarton ring modulator (QRM) coupling (spider symbol represents quarton). In quarton coupling, the transmon on the right has been linearized into a resonator [6]. Color blue represents resonator, pink represents coupler, and purple represents transmon qubit.



Comparing the limits of state-of-art dispersive readout versus proposed QRM coupler readout a) QRM coupler can reach high readout fidelity in nanoseconds, compared to about 50 ns for fastest dispersive readout. b) QRM coupler can accommodate large kappa for nanosecond-scale resonator ringdown compared to about 80 ns for largest kappa dispersive readout.

FURTHER READING

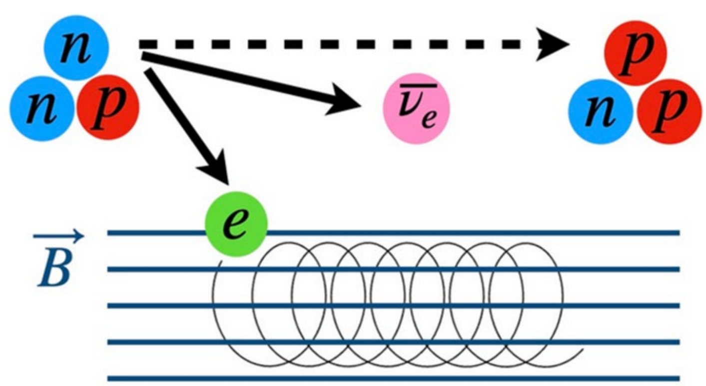
[1] Y. Ye, K. Peng, M. Naghiloo, G. Cunningham, K. P. O'Brien. "Engineering Purely Nonlinear Coupling Using a Quarton" Phys. Rev. Lett. 127, 050502 (2021)

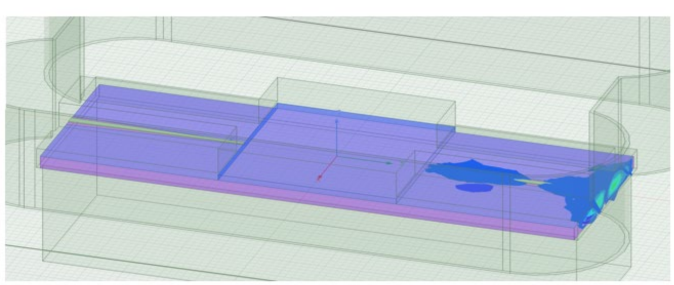
High frequency Josephson traveling wave parametric amplifiers for neutrino mass measurement

J. Wang, W. Van De Pontseele, K. Serniak, P. Harrington, J. Qiu, K. Peng, J. A. Formaggio, W. D. Oliver, K. P. O'Brien (accepted by PRX Quantum)
Sponsorship: MIT-CQE Doc Bedard Fellowship, U.S. Department of Energy Science Office (DE-FOA-0002110)

The neutrino mass is one of the most important open questions in particle physics, as neutrinos may have significantly impacted galaxy cluster formation in the early universe. Neutrino mass measurement experiments utilizing Cyclotron Radiation Emission Spectroscopy (CRES) have a weak output signal at 27 GHz of about 1 fW in power. This requires a signal-to-noise ratio 10 to 20 times greater than currently achieved per receiver antenna, as well as signal triggering within 10 microseconds to achieve the desired energy resolution. Hence, there is a pressing need for low-noise, tunable, and high-gain amplifiers, such as the Josephson traveling wave parametric amplifier (JTWPA), which is widely used for single photon level readout in superconducting quantum computer systems. These chip-based amplifiers can attain high signal gain (>20 dB) over several gigahertz of bandwidth with near-ideal quantum efficiency, and their frequency bandwidth can be tailored to a wide range of applications, such as quantum information processing, dark matter searches, and fundamental particle physics.

Here we show simulation and measurement results of a JTWPA designed to operate at high frequencies for neutrino mass determination. We also propose steps toward integrating the JTWPA into the neutrino mass measurement chain. We aim to achieve an electron antineutrino mass sensitivity on the order of 40 meV, which will surpass the sensitivity of the most recent Katrin result (0.7 eV at 90% confidence level) by an order of magnitude, and provide evidence for mass ordering in the neutrino sector. These results may help us extend the Standard Model of particle physics and significantly impact how we understand the history of the universe.





Noise Characterization, High-Fidelity Control, Waveguide QED, and Quantum Simulation with Superconducting Qubits

K. Serniak, D. Rosenberg, M. E. Schwartz, J. L. Yoder, J. I-J. Wang, J. A. Grover, S. Gustavsson, T. P. Orlando, W. D. Oliver

Sponsorship: IARPA, DARPA, LPS, DOE, NSF, MITLL

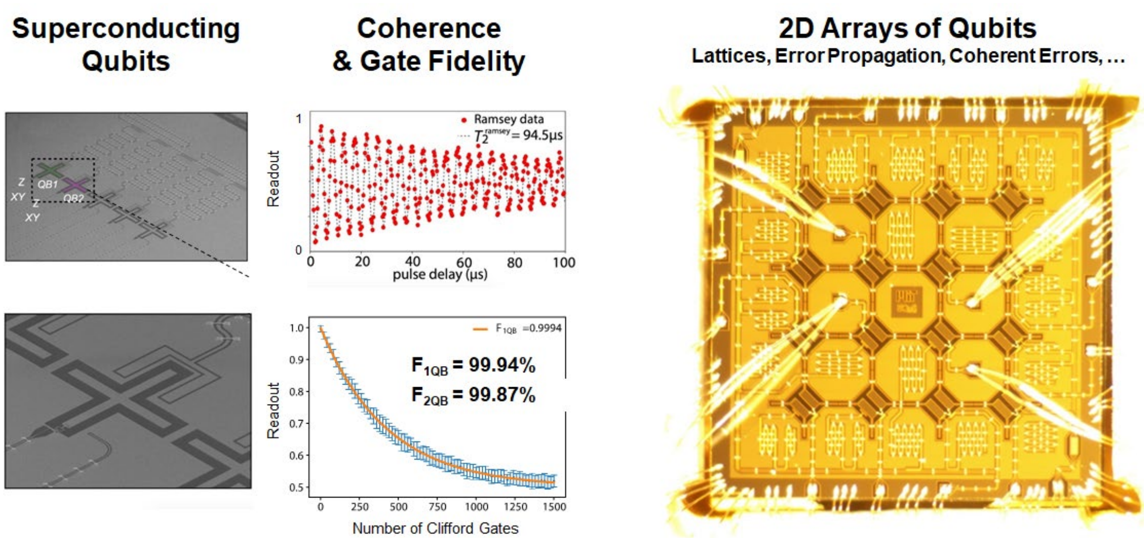
Superconducting qubits are electronic circuits comprising lithographically defined Josephson tunnel junctions, inductors, capacitors, and interconnects. Their potential for lithographic extensibility, compatibility with microwave control, and operability at nanosecond time scales place this modality at the forefront of contemporary quantum computation. The research in EQuS spans single devices to larger-scale systems.

Understanding the different sources and their spectral properties is key to building larger systems. We studied how qubit geometry can reduce flux noise (Phys. Rev. Applied **13**, 054079 (2020)); how noise spectroscopy can be extended to higher excited states (Nature Comm. **12**, 967 (2021)); and how to extract spatiotemporal correlations in noise (PRX Quantum **1**, 010305 (2020)). Moreover, we demonstrated that ionizing radiation from nearby radioactive materials and cosmic rays impact qubit coherence (Nature **584**, 551 (2020)), a key consideration in the design of fault-tolerant machines.

We developed new control methods on small-scale processors. In one experiment, we demonstrated nonadiabatic, baseband control of a small gap qubit, eliminating the need for pulsed-microwave control. (Phys. Rev. X **10**, 041051 (2020)). We similarly used baseband control and a qubit-coupling element to achieve state-of-the-art two-qubit gate fidelity (Phys. Rev. X **11**, 021058 (2021)).

We explored the use of waveguide quantum electrodynamics (wQED) and "giant atoms" – qubits coupled to a waveguide at multiple points (Nature **583**, 775 (2020)) and the generation of entangled photons called N00N states (Sci. Adv. **6**, eabb8780 (2020)). These could be a key ingredient for quantum interconnects and teleportation protocols between distant quantum processors.

Finally, we performed hybrid analog-digital computations on a strongly interacting 3×3 superconducting qubit array emulating a 2D hard-core Bose-Hubbard lattice (Nature Physics 2021).



A 10-kg object prepared close to its motional quantum ground state

C. Whittle, E. D. Hall, S. Dwyer, N. Mavalvala, V. Sudhir
Sponsorship: NSF

The preparation of macroscopic objects in pure quantum states is an outstanding challenge, with implications for fundamental quantum physics and precision measurements. Recent advances in laser cooling have seen progressively larger and more complex systems cooled to their motional ground state, all the way to nanomechanical. However, oscillators in the milligram-and-higher mass scale have mechanical resonances at much lower frequencies than the technologically achievable scattering rates required for efficient laser sideband cooling. Measurement-based feedback cooling addresses this challenge by using low-noise measurements and actuation to steer an object to a pure quantum state.

Advanced LIGO represents the state-of-the-art in precision displacement sensing. These gravitational-wave detectors are Michelson interferometers, comprised of two 4 km-long Fabry–Perot arm cavities formed by 40 kg mirrors that hang on fused silica fibers. The differential motion between the lengths of each arm cavity forms a mechanical oscillator with a reduced mass of 10 kg, sensed by the Michelson interferometer. At the intrinsic mechanical resonance of 0.43 Hz of the silica mirror suspension, their displacement fluctuates due to the presence of 10^{13} thermal phonons. Advanced LIGO's imprecision noise reaches a minimum of 2×10^{-20} m/√Hz around 100–200 Hz, dominated by quantum shot noise, which gets suppressed ~3 dB by injection of squeezed vacuum. Such sensitivity is equivalent to resolving the zero-point motion of the oscillator with ~125 dB signal-to-noise ratio and approaches the requirement to feedback cool the oscillator to its quantum ground state.

We have used feedback control to first trap the oscillator within the optimal 100–200 Hz range, before increasing feedback-mediated damping to suppress the oscillator motion to an average phonon occupation of 10.8, corresponding to the 10 kg oscillator spending about 10% of its time in the quantum ground state.

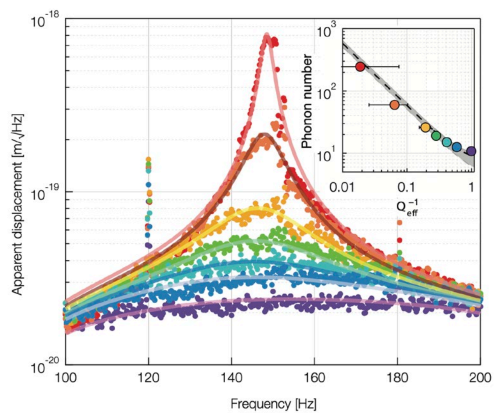


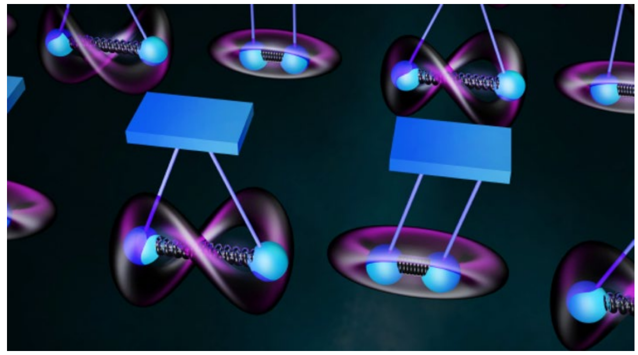
Figure 2 Displacement spectrum of the 10 kg optically trapped oscillator as it is progressively damped by feedback. Inset shows average phonon number inferred from fits (solid lines) to the spectra.

FURTHER READING

C. Whittle, E. D. Hall, S. Dwyer, N. Mavalvala, V. Sudhir (and the LIGO Instrument Science Group), Science 372, 1333 (2021)

Quantum Register of Fermion Pairs

Thomas Hartke, Botond Oreg, Ningyuan Jia, Martin Zwierlein



We realized a quantum register formed by hundreds of atom pairs, where quantum information is stored in the motion of fermion pairs. This leads to coherence times on the scale of ten seconds. The robustness of the register is owed to the Pauli principle, forcing the fermionic atoms to obey exchange symmetry. The same principle underlies the periodic system of the elements and lends stability to neutron stars. Achieving long coherence times is crucial to advancing quantum computers to the point where they can solve tasks impossible to solve on a classical computer.

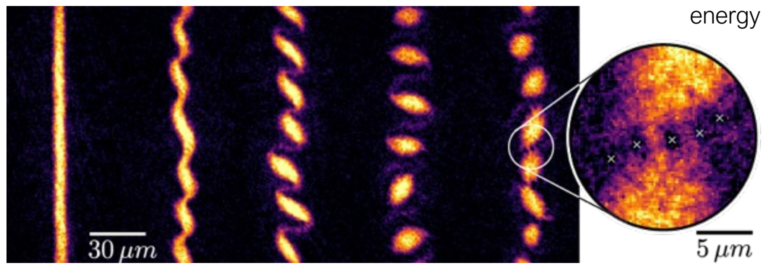
We demonstrate universal control of the vibrational pair qubits by modulating interactions between the atoms. Via coherent conversion of free atom pairs into tightly bound molecules, we tune the speed of motional entanglement over three orders of magnitude, yielding 10^4 Ramsey oscillations within the coherence time. The methods open the door towards fully programmable quantum simulation and digital quantum computation based on fermions.

FURTHER READING

Nature **601**, 537–541 (2022), arXiv:2103.13992

Crystallization of Bosonic Quantum Hall States

Biswaroop Mukherjee, Airlia Shaffer, Parth B. Patel, Zhenjie Yan, Cedric C. Wilson, Valentin Crépel, Richard J. Fletcher, Martin Zwierlein



The dominance of interactions over kinetic energy lies at the heart of strongly correlated quantum matter, from fractional quantum Hall liquids, to atoms in optical lattices and twisted bilayer graphene. In this work, we study the purely interaction-driven dynamics of a Landau gauge Bose-Einstein condensate in and near the lowest Landau level (LLL). We observe a spontaneous crystallization driven by condensation of magneto-rotons, excitations visible as density modulations at the magnetic length. Increasing the cloud density smoothly connects this behaviour to a quantum version of the Kelvin-Helmholtz hydrodynamic instability, driven by the sheared internal flow profile of the rapidly rotating condensate. At long times the condensate self-organizes into a persistent array of droplets, separated by vortex streets, which are stabilized by a balance of interactions and effective magnetic forces.

FURTHER READING

Nature **601**, 58 (2022)