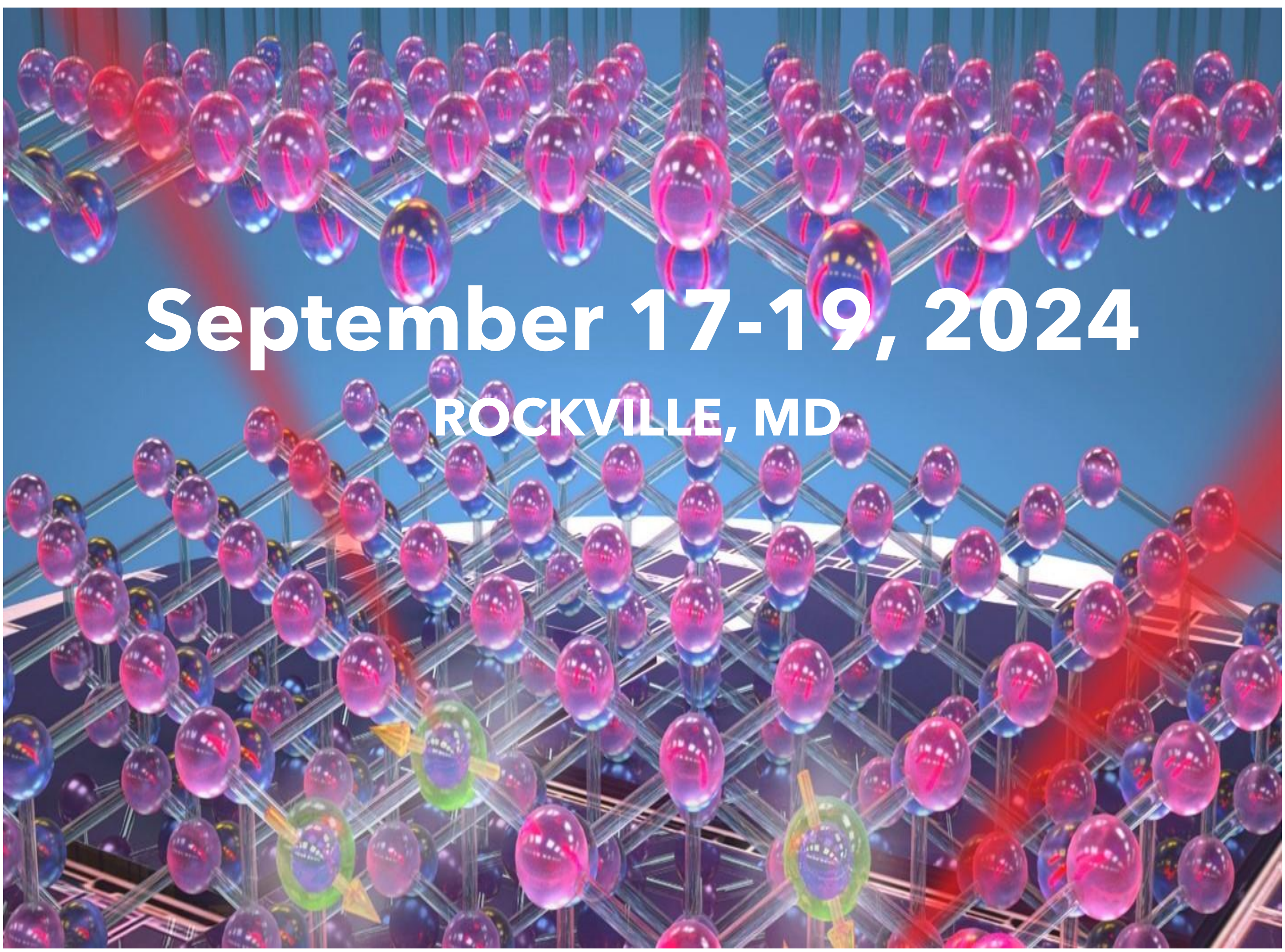
Principal Investigators Meeting

NATIONAL QUANTUM INFORMATION SCIENCES RESEARCH CENTERS



September 17-19, 2024

ROCKVILLE, MD

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Acronyms

Acronyms	Definition
SC	Office of Science
ASCR	Advanced Scientific Computing Research Program
BES	Basic Energy Sciences Program
BER	Biological and Environmental Research Program
FES	Fusion Energy Sciences
HEP	High Energy Physics
NP	Nuclear Physics
C^2QA	Co-design Center for Quantum Advantage
Q-NEXT	Next Generation Quantum Science and Engineering
QSA	Quantum Systems Accelerator
QSC	The Quantum Science Center
SQMS	Superconducting Quantum Materials and Systems Center

Agenda: National QIS Research Centers' PI Meeting

DAY 1 – 17 September 2024

A full-day event of joint presentations, posters, demos, panels recognizing the organization, achievements and future vision of the DOE NQISRCs

8:00am - Breakfast (*Outside Plaza Ballroom*)

9:00am – 9:30am - Welcome and opening remarks (*Plaza Ballroom)*

- Associate Director of Advanced Scientific Computing Research, Ceren Susut
- Under Secretary of Science and Innovation, Geraldine Richmond

9:30am – 10:00am - Impact of the NQISRC on the QIS landscape (*Plaza Ballroom)*

- *How the centers came to life, brought transformational impacts to QIS and beyond, and our vision for the future*
    - Anna Grassellino, SQMS, Centers Executive Council Chair

10:00am – 10:20am - Center-scale technical accomplishments (*Plaza Ballroom)*

- *Technical stories of success where Centers advanced quantum computing, sensing and communication*
    - David Awschalom, Q-NEXT

10:20am – 10:40am - Break

10:40am – 11:00am - Advancing Facilities and Instrumentation for QIS (*Plaza Ballroom)*

- *Creating new cutting-edge tools and leveraging the world's most advanced facilities to advance QIS*
    - Andrew Houck, C^2QA

11:00am – 11:20am - Partnering with Industry and Academia to Accelerate Innovation and Impact (*Plaza Ballroom)*

- *How our multidisciplinary collaborations have successfully moved across several levels of the Science and Technology Innovation Chain*
    - Travis Humble, QSC

11:20am – 11:40am - Ecosystem stewardship and workforce development at the NQISRCs (*Plaza Ballroom)*

- *Leading and complementing the National and International QIS Ecosystem*, *creating a QIS workforce*
    - Bert de Jong, QSA

11:40am – 12:00pm - Coordinating Operations In a Diverse Ecosystem (*Plaza Ballroom)*

- *Center streamlined operational lessons learned and coordination mechanisms*
    - Kimberly McGuire, Chief Operations Officers Council Chair

12:00pm – 1:30pm – Lunch: Five centers workforce, communication and outreach strategy and highlights (*Atrium*)

- *Working lunch topic: reporting out on what we have accomplished and looking towards forward initiatives*
    - Leah Hesla (Q-NEXT), Megan Ivory (QSA), Silvia Zorzetti (SQMS), Sasha Boltasseva (QSC), Danielle Roedel (C^2QA)

1:30pm – 3:30pm - Coffee and Poster & Showcase Session (*Roosevelt/Madison*) **–**

- *An opportunity to engage with Centers' scientists and learn more about their achievements in QIS*

3:30pm – 4:30pm - Panel discussion - Accelerating impact by centers on industry (*Plaza Ballroom*)

- *Moderator: Celia Merzbacher, QED-C*
    - Cameron Kopas (SQMS, Rigetti), David Kistin (QSA, Sandia), Dennis Tom (QSC, Microsoft), Sarah Sheldon (C^2QA, IBM), Mark Ritter (C^2QA, IBM), Thaddeus Ladd (Q-NEXT, HRL)

4:30pm – 5:00pm - Closing Remarks

5:00pm - Adjourn

DAY 2 – 18 September 2024

A full-day event focused on the technical progress that center research and development activities realized.

8:00am - Breakfast (*Outside Plaza Ballroom*)

9:00am – 12:50pm - Center Thrust Leaders and Deputy Directors: main research directions and achievements (*Plaza Ballroom)*

- **9:00am – 9:40am - C^2QA:** Andrew Houck, Nathan Wiebe, Michael Hatridge, Mark Ritter
- **9:40am – 10:20am - SQMS:** Alexander Romanenko, Roni Harnik, Silvia Zorzetti, Jim Sauls
- **10:20am – 11:00am - QSA:** Christopher Monroe, Irfan Siddiqi, Adam Kaufman

11:00am – 11:30am - Break

- **11:30am – 12:10am - Q-NEXT:** Joe Heremans, Jennifer Dionne, Mark Eriksson
- **12:10pm – 12:50pm - QSC:** Michael McGuire, Aaron Chou, and Andrew Sornborger

12:50pm – Lunch *(Atrium)*

2:00pm – 2:30pm - Cross-Center Collaboration Examples and Quantum S&T Innovation Chain Database *(Plaza Ballroom)*

Murthy, Kasra, Chen

2:30pm – 3:30pm - Technical Highlights from early and mid-career researchers *(Plaza Ballroom)*

- **QSA -** Annette Carroll (University of Colorado, Graduate Student)
- **Q-NEXT -** Alan Dibos (Argonne, Staff Scientist)
- **SQMS -** Lin Zhou (Ames National Lab, Staff Scientist)

- **C²QA -** Mingzhao Liu (BNL, Mid-Career)
- **QSC -** Olivia Liebman (UCLA)

3.30pm – 3:45pm - Coffee Break

3:45pm – 4:45pm - Technical Highlights from early and mid-career researchers *(Plaza Ballroom)*

- **QSA -** Ilan Rosen (MIT, Senior Postdoc)
- **Q-NEXT -** Anchita Addhya (University of Chicago, Graduate Student)
- **SQMS -** Hank Lamm (Fermilab, Associate Scientist)
- **C²QA -** Uysal "Tuna" Mehmet (Princeton, Early Career)
- **QSC -** Vahagn Mkhitaryan (Purdue University)

4:45pm – 5:00pm - Closing Remarks

5:00pm - Adjourn

DAY 3 – 19 September 2024

Half-day event focused on discussion of future challenges, goals and vision

8:00am - Breakfast (*Outside Plaza Ballroom*)

9:00am – 9:30am - Deputy Directors Panel Discussion/Summary on Areas of Synergy and Coordination *(Plaza Ballroom)*

- Kai-Mei Fu, Jens Koch, Dan Stick, Jen Dionne, Vivien Zapf

9:30am – 10:30am - Collaborative breakout sessions

Charge question: What are the next highest priority challenges and opportunities in each research area? And what emerging opportunities for collaborative and coordinated efforts?

- **Materials and devices for QIS – QSC** *(Madison)*
    - Vivien Zapf
    - Co-chairs: Alan Tennant (QSC), Akshay Murthy (SQMS), Dirk Englund (QSA), Supratik Guha (Q-NEXT), Michael Hatridge (C²QA)

- **Quantum systems integration – QSA** *(Roosevelt)*
    - Dan Stick
    - Co-chairs: C²QA (Chen Wang), Alan Dibos (Q-NEXT), Mollie Schwartz (QSA), Alberto Marino (QSC), David Van Zanten (SQMS)

- **Quantum algorithms, simulation, tools – C2QA** *(Washington Theater)*
    - Isaac Chuang
    - Co-chairs: Eleanor Rieffel (SQMS), Yigit Subasi (QSC), Isaac Chuang (C²QA), Ivan Deutsch (QSA), Giulia Galli (Q-NEXT)

- **Quantum sensing – SQMS** *(Regency)*
    - Bianca Giaccone

    - Co-chairs: Daniel Baxter (QSC), Kent Irwin (Q-NEXT), Bianca Giaccone (SQMS), Kai-Mei Fu (C^2QA), Vladan Vuletic (QSA)

- **Quantum communication and networking – Q-NEXT** *(Eisenhower)*
    - Paul Kwiat
    - Co-chairs: Paul Kwiat (Q-NEXT), Yao Lu (SQMS), Gabriella Carini (C^2QA), Jungsang Kim (QSA), Vlad Shalaev (QSC)

10:30am – 10:45am - Break

10:45am – 11:45am - Resume breakout rooms

11:45am – 12:15pm - Reports from breakouts *(Plaza Ballroom)*

12:15pm – 12:30pm - Closing Remarks

12:30pm - Adjourn

Posters: NQISRC Overview Posters

C^2QA

C^2QA Overview

Andrew Houck[1,2]

[1]Princeton University; [2]Brookhaven National Laboratory

The Co-design Center for Quantum Advantage (C^2QA) aims to overcome the limitations of today's noisy intermediate scale quantum (NISQ) computer systems by applying quantum co-design principles. As materials scientists are uncovering the microscopic mechanisms behind quantum computational errors, other C^2QA researchers are designing and optimizing devices to improve performance parameters, including the amount of time before errors overwhelm quantum computations and the distance over which quantum systems can communicate. Software and algorithms experts are simultaneously leveraging the latest hardware advances to achieve quantum advantage for scientific computations in high-energy, nuclear, chemical, and condensed matter physics. Major breakthroughs include record coherence in superconducting qubits, the first indistinguishable single photon generation attached to a quantum memory, and an entirely new class of quantum algorithms. C^2QA also leads outreach and ecosystem stewardship events, including QIS faculty training across 45 MSIs, summer schools at all educational levels, and the all-center quantum career fair. Looking forward, as every quantum platform reaches limits on how many qubits can be placed in a single module, C^2QA is focused on engineering modular systems to achieve quantum advantage by improving both individual modules and architectures for connecting them.

Q-NEXT

Q-NEXT: Advancing Science for Breakthroughs in Quantum Communication, Sensing and Computing

David D. Awschalom[1,2]

[1]Argonne National Laboratory; [2]University of Chicago

https://q-next.org/

Q-NEXT is developing the science and technology for controlling, storing, and transmitting quantum information for scientific breakthroughs in fundamentally secure communications, networks of ultraprecise sensors, and interconnecting future quantum computers. In its four years of operation, the Q-NEXT center has launched two national quantum foundries, demonstrated novel and high-performance qubit platforms, installed a quantum computing testbed, and developed the science and technology that will help enable quantum networks. Q-NEXT has collaborated across industry, academia and national laboratories toward a roadmap, formally delivered to the Department of Energy, for achieving impact from quantum interconnect technology. The center has established itself at the forefront of the national quantum ecosystem through unique research experiences for students and educational tools to teachers and by engaging the public through popular quantum-themed events. As it looks ahead, Q-NEXT will draw on its foundation of scientific results and physical facilities to reinforce a domestic supply of quantum materials and devices for research and to accelerate quantum technology intro practice through collaboration with established and emerging companies — all toward U.S. leadership in this critically important field.

QSA

QSA – Quantum Systems Accelerator

Bert de Jong[1]

[1]Lawrence Berkeley National Laboratory

https://quantumsystemsaccelerator.org/

The Quantum Systems Accelerator (QSA) catalyzes national leadership in quantum information science (QIS) through co-design of devices, algorithms and engineering solutions to deliver meaningful scientific quantum advantage for Department of Energy (DOE) applications. The QSA is a multi-disciplinary team of recognized leaders in QIS dedicated to driving the field forward. This team develops advanced quantum systems in three technology areas—neutral atoms, trapped ions, and superconducting circuits—with reduced noise and errors. To scale quantum simulation platforms to sizes and fidelities capable of probing important scientific questions, the team develops extensible and high-fidelity control systems and interconnects. These advances produce quantum systems that explore the quantum technology trade space and to form the basic science foundations that accelerate the maturation of the quantum industry.

Through co-design, the team develops new algorithms and error mitigation and correction techniques for physical simulations on quantum computing platforms, and approaches to benchmark and verify the quantum advantage of systems. QSA's interdisciplinary teams utilize the quantum computing and sensing capabilities in the center to explore important Department of Energy relevant problems in many-body physics, chemistry and high-energy physics.

The QSA aims to demonstrate meaningful scientific quantum advantage. The QSA is charting a path beyond NISQ-era proof-of-concept demonstrations toward extensible, impactful, general-purpose quantum computing and sensing.

QSC

Quantum Science Center

Travis Humble[1]

[1]Oak Ridge National Laboratory

The Quantum Science Center is advancing scientific discovery to radically accelerate secure, energy-efficient computing and maintain American leadership in fundamental and applied science.

Through a partnership of 20 universities, companies, and national laboratories, more than 300 staff, faculty, and students are working together to discover exotic, error-resistant states of matter to drive new materials, devices, and methods that are both resilient and scalable. These “topological” devices and systems harness the extraordinary properties of quantum entanglement to encode, store, and process quantum information. Such research is only possible with the powerful instruments available from DOE user facilities, including the Frontier supercomputer and Spallation Neutron Source, both of which are co-located with the QSC at Oak Ridge National Laboratory. To efficiently advance scalable and coherent quantum information systems, QSC researchers of all levels follow a co-design philosophy that involves coordination across the Center’s initiatives, as well as close collaboration with industry partners and other stakeholders from the earliest stages of development through the completion and distribution of novel technologies to the marketplace. Additionally, the QSC is creating new opportunities across the national QIS ecosystem for engagement, outreach and workforce development; by actively engaging students and postdoctoral associate in research activities, the QSC offers a rich environment for professional development and ensures the next-generation of researchers are capable of inheriting the quest to realize the potential of quantum mechanics to vastly improve our world.

SQMS

Research Efforts Across the SQMS center

Anna Grassellino[1]

[1]Fermi National Accelerator Laboratory

https://sqmscenter.fnal.gov/

SQMS brings together more than 500 experts from 34 partner institutions—national laboratories, academia and industry—in a mission-driven, multidisciplinary collaboration that integrates deep expertise in quantum information science, material science, applied and theoretical superconductivity, computational science, particle and condensed matter physics, cryogenics, microwave devices and controls engineering, industry applications and more. Our research focuses on attacking the major cross-cutting challenge in the field of QIS of extending the lifetime of quantum states, or the coherence time. Understanding and mitigating the physical processes that cause decoherence and limit the performance of superconducting qubits is critical to realizing next-generation quantum computers and sensors. Decoherence makes performing precise calculations with few to no errors a nontrivial task. This phenomenon is an obstacle researchers need to overcome to make quantum computers a viable technology. The SQMS Center is taking a materials science-based approach to tackle this challenge. The Center has built a first-of-its-kind, broad coalition of experts studying quantum devices at the frontier of coherence, using the world’s most advanced characterization tools, including DOE accelerator-based user facilities. Leveraging Fermilab’s unique expertise in building particle accelerators and cryogenics systems, the SQMS Center aims to bring critical technological capabilities to the QIS field, to scale up complex quantum systems successfully. The Center brings together a coalition of hardware and applied researchers working in co-design, exploring early-stage applications of quantum technologies. In alignment with Fermilab’s core mission in particle physics, the Center has already demonstrated the first applications of quantum sensors as detectors for new particles with world-leading sensitivity.

C2QA

A Unitary Encoder of Surface Code

Pei-Kai Tsai[1], and Shruti Puri[1]

[1]Yale University

The quantum surface code is a promising candidate to achieve fault-tolerant quantum computation and has been realized in both superconducting qubits and Rydberg atomic arrays. Recently, Rydberg-atom qubits have demonstrated scalability and the capability of long-range interactions; however, their measurements are slower and have lower fidelities. Consequently, unitary encoders are a potential alternative for encoding logical information into surface codes, bypassing the need for traditional stabilizer measurements.

In this work, we propose a unitary encoder circuit based on the unitary code conversion between rotated and regular surface codes. Our approach utilizes a depth-4 circuit to double the code size, offering a logarithmic time complexity in the final code size and with a 50% lower constant factor compared to the previous approach based on the multi-scale entanglement renormalization ansatz (MERA). While this approach, like other unitary encoding approaches, is not fault-tolerant, we numerically investigate its breakeven performance. We also explore the potential of our encoding scheme for applications such as magic state injection where the standard lattice-surgery-based method also has an overall code distance limited by the initial code size.

C2QA

Advancing Quantum Computing with the Aid of Materials Science

Shannon Bernier[1], Elizabeth Hedrick[1], Evan Crites[1], Carsen Koppel[2], Abby Neill[1], Satya Kushwaha[1], and Tyrel M. McQueen[1]

[1]Johns Hopkins University; [2]Brookhaven National Laboratory Summer Student

Advancements in quantum computing often come out of multidisciplinary teams. Here, we present four ways in which materials science is advancing QISE. The archetypal example of this work is in the design of new materials, such as new qubit host materials, superconductors for use in transmons, and quantum transducers. From work on understanding dopant and defect chemistry on single ion qubits to perfecting transducer candidates via new annealing techniques and isotopic enrichment, this area is one in which our center has excelled. However, C2QA researchers have also lent insight into refinements to existing devices; for example, by suggesting alternate materials for use in Josephson junctions and identifying superconductor candidates with oxidation resistance. We have also developed new test methods for these candidates, allowing faster and more accurate screening of materials for future devices. Finally, materials researched by C2QA have provided simulation candidates for NISQ devices such as quantum annealers. By carefully designing materials with architectural similarities to these devices, we have enabled near-term validation of quantum computation for materials research.

C2QA

Development of a Generic Multimodal Scanning Probe Testbed

Patrick Forrester[1], Yuan Cao[1], Federico Maccagno[1], Taeho Kim[1], Guilhem Ribeill[2], EliseAnne Koskelo[1], Zhuozhen Cai[1], Jiachen Yu[3], Christopher Cheung[3], Martin Gustafsson[2], Ali Yazdani[3], and Amir Yacoby[1]

[1]Harvard University; [2]BBN-RTX; [3]Princeton University

New sensor development for the characterization of quantum materials and devices is crucial to investigating contemporary questions in condensed matter physics and quantum information science. Moreover, various experimental challenges such as sensitivity to air and thermal cycling, twist angle disorder, and charge inhomogeneity make comparisons between devices and experimental runs difficult. Multimodal measurements overcome these challenges, while enabling increased throughput. In this poster, I will present progress on the development of a generic multimodal scanning probe microscopy platform we call 'multiprobe microscopy.' Our multiprobe microscope allows us to scan a generic ensemble of silicon nanofabrication compatible sensors close to samples in cryogenic environments with vector magnetic field control and electronic access from DC to ~ 10 GHz. I will show preliminary results benchmarking this system, highlighting progress on integrating scanning single electron transistor (SET) as well as scanning superconducting resonator microscopy modalities into this platform. In addition, we will discuss the relevance of this new tool to pressing problems in quantum information science with an emphasis on superconducting qubit systems.

C^2QA

Dispersive Non-reciprocity Between a Qubit and a Cavity

Sean van Geldern[1] and Chen Wang[1]

[1]University of Massachusetts - Amherst

The dispersive interaction between a qubit and a cavity is ubiquitous in circuit and cavity quantum electrodynamics. It describes the frequency shift of one quantum mode in response to excitations in the other, and in closed systems is necessarily bidirectional, i.e.~reciprocal. Here, we present an experimental study of a non-reciprocal dispersive-type interaction between a transmon qubit and a superconducting cavity, arising from a common coupling to dissipative intermediary modes with broken time reversal symmetry. We characterize the qubit-cavity dynamics, including asymmetric frequency pulls and photon shot-noise dephasing, under varying degrees of non-reciprocity by tuning the magnetic field bias of a ferrite component in situ. Furthermore, we show that the qubit-cavity dynamics is well-described in a wide parameter regime by a simple non-reciprocal master-equation model, which provides a compact description of the non-reciprocal interaction without requiring a full understanding of the complex dynamics of the intermediary system. Our result provides an example of quantum non-reciprocal phenomena beyond the typical paradigms of non-Hermitian Hamiltonians and cascaded systems.

C^2QA

Error Detection and Error Correction with Superconducting Circuits: The Microwave Cavity Dual-Rail

James D. Teoh[1], Patrick Winkel[1], Harshvardhan K. Babla[1], Benjamin J. Chapman[1], Jahan Claes[1], Jacob Curtis[1], Stijn J. de Graaf[1], John W. O. Garmon[1], William D. Kalfus[1], Yao Lu[1], Aniket Maiti[1], Kaavya Sahay[1], Neel Thakur[1], Takahiro Tsunoda[1], Yue Wu[1], Sophia H. Xue[1], Luigi Frunzio[1], Steve M. Girvin[1], Shruti Puri[1], and Robert J. Schoelkopf[1]

[1]Yale University

Quantum error correction is indispensable to the realization of fault-tolerant quantum computing since every quantum system is prone to physical errors. However, depending on the hardware architecture some types of errors are more likely than others, leading to an error hierarchy characteristic for each platform. In superconducting microwave cavities, single photon loss is the dominant error channel while the intrinsic dephasing times can exceed energy relaxation by orders of magnitude. To this end, we introduce the dual-rail cavity qubit that encodes logical information in the single-photon subspace of two superconducting microwave cavities. With this encoding, leakage out of the computational subspace caused by photon loss and gain is detectable and thus convertible into erasure errors. Since erasure errors are unknown errors with known location, they have a significantly higher threshold and better scaling with code distance compared to Pauli errors. For the detection of these leakage events, as well as for logical control and readout, we use parametric beamsplitter interactions between the cavities and the dispersive interaction to transmon ancillae.

C²QA

Exploring Quantum Materials with Ultrabroadband Infrared-THz Nanoscopy

Lukas Wehmeier[1,2], M. K. Liu[1,2], C. Zhou[1], A.K. Anbalagan[1], A.L. Walter[1], N.P. de Leon[3], M. Liu[1], S. Hulbert[1], D.N. Basov[4], and G.L. Carr[1]

[1]Brookhaven National Laboratory; [2]Stony Brook University; [3]Princeton University; [4]Columbia University

Infrared near-field nanospectroscopy provides unique capabilities for the exploration of the nanoworld as it combines the information density of optical techniques with the spatial resolution of atomic force microscopy of ~10 nm. However, while many fundamental material excitations have resonance energies in the order of a few 10 meV, broadband table-top near-field spectroscopy is typically limited to the energy range >80 meV. Employing intense synchrotron radiation, synchrotron-based infrared near-field spectroscopy largely lifts this limitation and enables nanoscale material studies in a much broader spectral range.

At the National Synchrotron Light Source II (NSLS II), we are currently commissioning a new infrared nanospectroscopy setup, which enables infrared nanospectroscopy in the spectral range from 175 cm^{-1} to 6000 cm^{-1} (22 meV - 744 meV; 5 THz - 180 THz). As our instrument currently is the only one covering such a broad spectral range, it provides unique opportunities for nanoscale material investigation. Here, we demonstrate this via polariton interferometry of the van der Waals material GeS and an hBN-MoO_3 hetero-bicrystal. Also, we present broadband infrared

nanospectroscopy of Ta films, the latter providing a central material platform for superconducting qubits.

As a future extension of our infrared nanospectroscopy capabilities at NSLS-II, we are developing a near-field microscopy setup that works at cryogenic temperatures (<5 K to 350 K) and high magnetic fields (<7 T). First results with this unique setup were obtained with table-top laser sources and provide unique insights into the high-momentum magneto-optics of graphene.

C^{2}QA

Hidden Hydrogen at Interfaces of Niobium and Tantalum Oxides for Quantum Applications

Jeffrey Dhas[1,2], Ekta Bhatia[3], Peter V. Sushko[1], Krishna P. Koirala[1], Aleksandra Biedron[3], Francisco Ponce[1], Drew J. Rebar[1], Zihua Zhu[1], Mingzhao Liu[4], Yingge Du[1], and Satyavolu S. Papa Rao[3]

[1]Pacific Northwest National Laboratory; [2]Oregon State University; [3]NY CREATES; [4]Brookhaven National Laboratory

Niobium and tantalum surface oxides have been postulated to contain the atomistic sources of quantum decoherence. We show that the oxide formed on the surface of Nb subjected to chemical mechanical planarization (CMP) shows a similar layered structure as Nb native oxide (with Nb_2O_5 on the surface, sub-oxides in the subsurface region, followed by bulk Nb^0 in the bulk) [1]. It is also thinner than the native oxide of Nb. Further, ^{18}O diffusion studies showed that (i) CMP-formed Nb oxide is far less permeable than native Nb oxide to oxygen, and that (ii) they both have [OH] accumulating under the Nb_2O_5. SIMS analyses have shown that Ta exhibits the same behavior as Nb, vis-à-vis [OH] in the sub-surface oxide region. The lower concentration of OH per unit area in Ta versus Nb is consistent with qubits exhibiting better coherence with Ta than with Nb wiring. $Nb^{18}O$ (grown at 150ºC) was exposed to a D_2O-saturated ambient. Subsequent SIMS analysis showed that OD and OH accumulate at the interface between Nb_2O_5 and Nb sub-oxides. We surmise that the [OH] species is a possible source of microwave loss for Ta and Nb. Characterization of damascene-Ta resonators shows good yield, and < 5% variation in center frequency. High-resolution TEM indicates the presence of unwanted oxides at the Si/TaN interface, and within the TaN, that can degrade Q. Studies are ongoing to quantify the change in Q in the absence of such oxides, and [OH].

[1] Crowley *et al.*, Phys. Rev. X **13**, 041005 (2023).

C^{2}QA

High-Fidelity Preparation of Ground-States and Gates Using Adaptive Ansätze and Tunable Pulses

Karunya Shirali[1], Sophia E. Economou[1], Edwin Barnes[1]

[1]Virginia Polytechnic Institute and State University

Two key challenges impede our ability to implement quantum computation: the finite coherence times of qubits and gate errors that limit the fidelity of circuit operations. We address these in a holistic way through two complementary approaches: algorithmic improvements that lead to a lower gate requirement (software) and by developing protocols for noise-robust quantum gates (hardware). Our team has developed quantum simulation algorithms that lead to short, efficiently structured ansätze for state preparation. These include ADAPT-VQE, which creates a problem-tailored ansatz on the fly and ctrl-VQE, which gives a pulse-schedule that is considerably shorter than any gate-based approach. In collaboration with C²QA partners, we have applied ADAPT-VQE to problems of interest to the DOE, with an emphasis on periodic systems that are ubiquitous in condensed-matter and high-energy physics. We are currently co-designing our algorithms to suit the hardware developed in the center. On the hardware side, we are developing protocols for error-robust entanglement of spin qubits and tailoring space-curve based quantum control techniques to generate noise-robust quantum gates for superconducting hardware.

C²QA

Hybrid Oscillator-qubit Quantum Processors: Instruction Set Architectures, Abstract Machine Models, and Applications

Yuan Liu[1,2 *], Shraddha Singh[3,*], Kevin C. Smith[4,3 *], Eleanor Crane[1], John M. Martyn[1], Alec Eickbusch[3,†], Alexander Schuckert[5], Richard D. Li[3], Jasmine Sinanan-Singh[1], Micheline B. Soley[6], Takahiro Tsunoda[3], Isaac L. Chuang[1], Nathan Wiebe[7,8,9], and Steven M. Girvin[3,‡]

[1]Massachusetts Institute of Technology; [2]North Carolina State University; [3]Yale University; [4]Brookhaven National Laboratory; [5]NIST/University of Maryland; [6]University of Wisconsin-Madison, [7]University of Toronto; [8]Canadian Institute for Advanced Research; [9]Pacific Northwest National Laboratory; *These authors contributed equally (ordered alphabetically); † Present affiliation: Google Quantum AI; ‡Corresponding author

https://doi.org/10.48550/arXiv.2407.10381

Quantum computing with discrete variable (DV, qubit) hardware is approaching the large scales necessary for computations beyond the reach of classical computers. However, important use cases such as quantum simulations of physical models containing bosonic modes (e.g., lattice gauge theory), and quantum error correction are challenging for DV-only systems. Hardware containing native continuous-variable (CV, oscillator) systems has received attention as an alternative approach, yet the universal control of such systems is non-trivial. In this work, we demonstrate that hybrid CV-DV hardware offers great advantages in meeting these challenges. We provide a pedagogical introduction to CV-DV systems and the multiple abstraction layers needed to produce a full software stack connecting applications to hardware. We present a variety of new hybrid CV-DV compilation techniques, algorithms, and applications, including the extension of quantum signal processing concepts to CV-DV systems and strategies to simulate systems of interacting spins, fermions, and bosons. To facilitate the development of hybrid CV-DV processor systems, we introduce formal Abstract Machine Models and Instruction Set Architectures -- essential abstractions that enable developers to formulate applications, compile algorithms, and explore the potential of current and future hardware for realizing fault-tolerant circuits, modules, and processors. Hybrid CV-DV quantum computations are beginning to be performed in superconducting, trapped ion, and neutral atom platforms, and large-scale experiments are set to be demonstrated in the near future. We present a timely and comprehensive guide to this relatively unexplored yet promising approach to quantum computation and provide an architectural backbone to guide future development.

C²QA

Observation of Discrete Charge States of a Coherent Two-Level System in a Superconducting Qubit

Bao-Jie Liu[1], Ying-Ying Wang[1], Tal Sheffer[1], and Chen Wang[1]

[1]University of Massachusetts-Amherst

We report observations of discrete charge states of a coherent dielectric two-level system (TLS) that is strongly coupled to an offset-charge-sensitive superconducting transmon qubit. We measure an offset charge of 0.072e associated with the two TLS eigenstates, which have a transition frequency of 2.9 GHz and a relaxation time exceeding 3 ms. Combining measurements in the strong dispersive and resonant regime, we quantify both transverse and longitudinal couplings of the TLS-qubit interaction. We further perform joint tracking of TLS transitions and quasiparticle tunneling dynamics but find no intrinsic correlations. This study demonstrates microwave-frequency TLS as a source of low-frequency charge noise.

C²QA

Parametric Controls for Quantum Modules, Single Qubit Gates, and Longitudinal Qubit Readout

Mingkang Xia[1], Jake Repicky[1], Girish Khumbar[1], Boris Mesits[1], Israa Yusuf[1], Gaurav Agarwal[1], and Michael Hatridge[1,2]

[1]University of Pittsburgh; [2]Yale University

In our work for the C²QA center, we have been exploring the use of parametric controls of all aspects of superconducting processors. In this poster, we will show, first, how we use SNAIL-based three-wave parametric couplers to build quantum modules with all-to-all local connections, and which can be scaled to larger arrays of qubits. Next, we show the use of the same parametric controls between a qubit and its readout mode to generate ideal, longitudinal readout of a qubit that, unlike cQED based readout, turns fully off when no controls are applied. Finally, we show that the idea of parametric driving can be extended to the transmon itself, where we can produce very fast single qubit gates by driving the qubit at ~1/3 its resonant frequency, which will potentially allow us to achieve fast gates with longer qubit lifetimes and reduced cryostat heating.

C²QA

Quantum Memory: A Missing Piece in Quantum Computing Units

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[1]Pacific Northwest National Laboratory; [2]University of British Columbia; [3]University of California, San Diego

Memory is an indispensable component in classical computing systems. While the development of quantum computing is still in its early stages, current quantum processing units mainly function as quantum registers. With the rapid scaling of qubits, it is opportune to explore the potential and feasibility of quantum memory across different substrate device technologies and application scenarios. In this work, we provide a full design stack view of quantum memory, from the elementary building blocks: quantum memory cells, to quantum memory devices and the quantum memory function units in the architecture of quantum processing units. We further propose programming models for the quantum memory units and discuss their possible applications.

C²QA

Quantum Simulation in the Path Integral Representation

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We provide a new paradigm for quantum simulation that is based on path integration that allows quantum speedups to be observed for problems that are more naturally expressed using the path integral formalism rather than the conventional sparse Hamiltonian formalism. We provide two novel quantum algorithms based on Hamiltonian versions of the path integral formulation and another for Lagrangians of the form $T - V(x)$. This Lagrangian path integral algorithm is based on a new rigorous derivation of a discrete version of the Lagrangian path integral. Our first Hamiltonian path integral method breaks up the paths into short timesteps. It is efficient under appropriate sparsity assumptions and requires a number of queries to oracles that give the eigenvalues and overlaps between the eigenvectors of the Hamiltonian terms that scales near optimally for simulation time t and error ϵ. The second approach uses long-time path integrals for near-adiabatic systems and has query complexity that scales as $O(1/\sqrt{\epsilon})$ if the energy eigenvalue gaps and simulation time is sufficiently long. Finally, we show that our Lagrangian simulation algorithm requires a number of queries to an oracle that computes the discrete Lagrangian that scales for a system with η particles in $D+1$ dimensions, in the continuum limit, quadratically in t and inversely with epsilon if $V(x)$ is bounded and finite and the wave function obeys appropriate position and momentum cutoffs. This shows that Lagrangian dynamics can be efficiently simulated on quantum computers and opens up the possibility for quantum field theories for which the Hamiltonian is unknown to be efficiently simulated on quantum computers.

C²QA

QuIRC: Co-design of Superconducting Quantum Interface Routing Card for Lattice Surgery of Surface Codes

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Facilitating the ability to achieve logical qubit error rates below physical qubit error rates, error correction is anticipated to play an important role in quantum computers. While many algorithms require millions of qubits to be executed with error correction, current superconducting qubit systems are on the order of hundreds of qubits. One of the most promising codes on the superconducting qubit platform is the surface code, requiring a attainable error threshold and the ability to perform universal fault-tolerant quantum computing with local operations via lattice surgery and magic state injection. Surface code architectures easily generalize to single-chip planar layouts due to their localized operations, however space and control hardware constraints point to limits on the number of qubits that can fit on one chip. Additionally, planar routing on single-chip architectures leads to serialization of otherwise commuting. Based on current trends in hardware, a potential solution envisioned is a distributed multi-chip architecture utilizing the surface. However, fault tolerant distributed quantum computing surfaces new challenges in optimizing inter-chip gates, managing collisions in networking between chips, and minimizing routing costs. We propose QuIRC, a superconducting Quantum Interface Routing Card for Lattice Surgery between surface code modules. Motivated by current trends in superconducting hardware, lattice surgery error thresholds of surface codes, and the parallelized layered computation model of Pauli Based Computation model, we propose QuIRC. QuIRC trades off system complexity by introducing a routing card for increased gate parallelism. We demonstrate reductions in ancilla routing transpilation, and decoder strain.

C[2]QA

Temperature and Magnetic-Field Dependence of Relaxation in a Fluxonium Qubit

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Flux and charge noise from defects on material surfaces and interfaces is known to limit the coherence of superconducting circuits, yet a complete understanding of their underlying physics is still lacking. The fluxonium circuit, which consists of a single Josephson junction shunted by a capacitor and a linear inductor, can be made with transition frequencies as low as tens of MHz. It has sensitivity near half-flux to both charge and flux noise, potentially resulting in the relaxation time T1 having contributions from both dielectric loss and low-frequency magnetic flux noise. Probing the response of an environmental noise bath to relevant thermodynamic quantities such as magnetic field and temperature should shed light on the nature of the bath constituents, offering a clearer path to mitigating their effects and improving coherence. Motivated by this, here we present temperature and in-plane magnetic field characterizations of a fluxonium qubit with a minimum frequency of ~50 MHz, utilizing T1 relaxometry as a noise probe. We observe new trends in the noise with temperature and magnetic field, which may provide further constraints for microscopic theories of flux and charge noise.

C2QA

Vortex Motion Induced Losses in Tantalum Resonators

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Tantalum (Ta) based superconducting circuits have been demonstrated to enable world-record qubit coherence times (T_2) and quality factors (Q) [1, 2], motivating a careful study of the microscopic origin of the remaining losses that limit their performance. We have recently shown [2] that the losses in Ta-based resonators are dominated by several types of surface and bulk saturable two-level systems (TLSs). We also observe that some devices exhibit loss that is exponentially activated at low temperature, despite the f act that they are fabricated from films that have a single crystal structure associated with the high-T_c BCC (α) phase of Ta. Specifically, dc resistivity measurements show a superconducting critical temperature (T_c) of over 4 K, while resonators fabricated from these films show losses that increase exponentially with temperature with an activation energy as low as 0.3 K. Here, we present a comparative study of the structural and thermodynamic properties of Ta-based resonators and identify free vortex motion loss as the source of thermally activated microwave loss. Through careful magnetoresistance and X-ray diffraction measurements, we observe that the increased loss occurs for films that are in the clean limit, where the superconducting coherence length (ξ) is shorter than the mean free path (l). Vortex motion-induced losses are suppressed for films in the dirty limit, which show evidence of structural defects that can pin vortices. We verify this hypothesis by explicitly pinning vortices via patterning and find that we can suppress the loss by microfabrication.

[1] Nature Communications, 12(1), 1779 (2021)
[2] Physical Review X 13, 041005 (2023)

Q-NEXT

Argonne Quantum Foundry

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https://q-next.org/

We will present our efforts in standing up a semiconductor materials-focused quantum foundry, providing for the standardization of materials to address the national supply chain of quantum grade solid-state materials platform for spin-defect based quantum technology. The Argonne Quantum Foundry provides a full-stack materials processing toolkit focused on developing quantum relevant material platforms like diamond, silicon carbide, and relevant oxides. We will highlight our recent advances in host material growth, novel etching techniques, membrane fabrication and heterogenous integration, and local spin-defect creation techniques that serve as the building blocks for scalable, interconnected quantum devices. In parallel, we will highlight our efforts in workforce development, in particular our interactions with internship programs including the DOE Science Undergraduate Laboratory Internship (SULI), Open Quantum Initiative (OQI) and the Break Through Tech Chicago (BTTC) program.

Q-NEXT

The Chicago Quantum Computing Testbed at Argonne National Laboratory

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Q-NEXT.org

Quantum dots in silicon-based heterostructures can host long-lived, well-isolated electron spin states in a mature, scalable semiconductor platform. Although multiple types of spin qubit encodings have demonstrated fault tolerant-compatible gate fidelities, progress towards quantum computation with Si spin qubits has been slowed by the difficulty of reliably fabricating high-quality devices. The Chicago Quantum Computing Testbed, a Q-NEXT collaboration with the Intel Quantum Computing Group, leverages Intel's industrial fabrication of Si quantum dot devices to study the scaling and applications of quantum dot qubits. Low-lying excited "valley" states in Si limit qubit fidelities; by studying valleys across many quantum dots, we can better understand how this parameter relates to the underlying material and engineer this parameter in scalable devices. Qubit manipulation through tradition spin resonance-style controls can lead to frequency crowding and heat load issues as quantum dot qubits scale. "Exchange-only" qubits encode quantum information in a decoherence-free subspace with three electron spins, controlled only with localized, baseband electrical pulses. A better understanding of how to operate and entangle systems of many exchange-only qubits will provide a path to a scalable quantum dot processor.

Q-NEXT

Diamond Membranes for Quantum Technologies

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https://q-next.org/

Diamond is a desirable host material for a variety of optically addressable spin qubit defects relevant for applications in quantum information science. Spin qubits, such as the negatively charged nitrogen-vacancy center (NV), are inherently tied to their local crystalline, charge, and nuclear spin environments making them ideal for quantum sensing applications. For other applications, such as quantum communication, spin qubits like group-IV vacancy complexes (e.g. SiV, GeV, SnV) exhibit excellent spin-photon characteristics but also require careful considerations during integration with the local host material. Overall, spin qubit defects in diamond suffer from stochastic synthesis approaches and challenging integration pathways with other classical and quantum technologies. Here, we present our versatile diamond membranes platform for applications in quantum sensing and communication. We discuss recent advances in host material growth, nanofabrication, and deterministic defect creation that address these challenges directly. Specifically, we will discuss the synthesis of a diamond membrane materials platform and cavity co-localized defects that serves as a great host for relevant spin qubit defects while being entirely tunable and deterministically transferable.

Q-NEXT

Engineering Dark Spin-Free Diamond Surfaces

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Nitrogen-vacancy (NV) centers in diamond are extensively utilized as quantum sensors for imaging fields at the nanoscale. The ultra-high sensitivity of NV magnetometers has enabled the detection and spectroscopy of individual electron spins, with potentially far-reaching applications in condensed matter physics, spintronics, and molecular biology. However, the surfaces of these diamond sensors naturally contain electron spins, which create a background signal that can be hard to differentiate from the target spin signal. In this study, we develop a surface modification approach that eliminates the unwanted signal of these so-called dark electron spins. Our surface passivation technique, based on coating diamond surfaces with a thin titanium oxide (TiO_2) layer, reduces the dark spin density from a typical value of 0.002 nm^{-2} to a value below that set by the detection limit of our NV sensors (0.0002 nm^{-2}). This reduction in dark spin density results in a two-fold increase in spin echo time of near surface NV centers. Furthermore, we derive a comprehensive spin model that connects dark spin depolarization with NV coherence, providing additional insights into the mechanisms behind the observed improvements. Our findings are directly transferable to other quantum platforms, including rare-earth doped hosts.

Q-NEXT

Engineering Molecular Qubits for Sensing and Communication

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From trapped atoms to atom-scale defects in semiconductors, spin qubits that can couple to photons underly a wide range of emerging quantum technologies. Molecular analogs of these systems provide a route for bottom-up atomistic design of qubit properties. Following demonstration of optically addressable molecular spin qubits that can be coherently controlled with microwaves [1], we have shown that both the spin and optical properties of this class of qubits can be modified by changing the ligand structure, the central metal atom, and host environment [2 - 4]. We highlight the design of new molecular materials with strongly spin-selective optical transitions and show how this property enables direct, all-optical readout and initialization of molecular ground-state spins. These results highlight the promise of molecular materials tailored toward compatibility with photonic technologies.

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[2] D. W. Laorenza, et al. JACS. **143**, 50 (2021).
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[4] D. W. Laorenza, et al. Chem. Sci. (2024)

Q-NEXT

Initial Stages of Development of Er-doped CeO_2 on Silicon as a Quantum Memory Platform

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https://q-next.org/

Erbium-doped cerium oxide ($Er:CeO_2$) is a promising defect-host combination for applications in quantum memories for wide-area fiber optic-based quantum networks, due to the telecom-compatible (~1.5 μm) 4f-4f optical transition of Er, predicted long electron spin coherence time for defects in CeO_2, and small lattice mismatch between silicon and CeO_2. Here we report on epitaxial $Er:CeO_2$ thin films grown on silicon by molecular beam epitaxy, with Er doping in the 1-100 ppm regime. We verify the CeO_2 host structure via thorough microstructural study, and then characterize the spin and optical properties of the embedded Er^{3+} ions as a function of doping density. Studying the Z_1-Y_1 optical transition near 1530.7 nm at 3.5 K with 2-3 ppm Er, we find spectral diffusion-limited homogeneous linewidths as narrow as 440 kHz, along with inhomogeneous linewidths of 10 GHz and optical excited state lifetimes of 3.5 ms. Performing

corresponding spin measurements of Er^{3+} in CeO_2, we demonstrate a spin relaxation time of 2.5 ms and a spin coherence time of 0.66 μs. Given these promising coherence results, we additionally discuss strategies for scalable, foundry-compatible integration of silicon photonic devices with $Er:CeO_2$. These strategies, including selective etching of MBE-grown CeO_2 and growth of $Er:CeO_2$ by atomic layer deposition, should allow for enhanced Er^{3+} ions photonic emission rates via integration with one-dimensional photonic cavities.

Q-NEXT

Integrating spin qubits within silicon carbide technologies

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Spin-based defects within semiconductors enable information processing and sensing technologies based on the quantum nature of electrons and atomic nuclei [1]. These spin qubit systems have a built-in optical interface that emits in the visible and telecom bands, retain their quantum properties over millisecond timescales or longer, and can be manipulated using a simple combination of light and microwaves. Silicon carbide (SiC) offers a mature technological platform for spin qubits with clear pathways to scalable quantum devices and broad compatibility with CMOS fabrication. We discuss recent advances in this area including the integration of single spin qubits with lifetime-limited single-photon emission into electronically active SiC devices [2], and the significant extension of spin coherence times [3] through isotopic engineering of the local nuclear spin environment [4].

We also demonstrate new vanadium-based spin qubits in SiC, which have host-agnostic orbital structures and can exhibit optical emission in the telecom O-band [5], and therefore could be naturally integrated into pre-existing telecommunications networks without the need for complicated frequency conversion schemes. With decreasing temperature, we observe a remarkable four-orders-of-magnitude increase in spin relaxation and identify the underlying relaxation mechanisms which involve a two-phonon Orbach process [6].

Finally, we demonstrate techniques for the removal and transfer of SiC layers in the tens-of-microns thickness range for heterogenous integration of hybrid quantum systems [7]. By employing new approaches for stressor layer thickness control, we demonstrate controlled spalling of 4H-SiC, the highest fracture toughness material spalled to date, and the coherent spin control of neutral divacancy (VV0) qubit ensembles.

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[3] C.P. Anderson et al., Sci. Adv. 8, 5 (2022).
[4] A. Bourassa, et al. Nat. Mater. 19, 1319 (2020).

[5] G. Wolfowicz et al., Sci. Adv. 6, 18 (2020).
[6] J. Ahn et al., arXiv: 2405.16303
[7] C.P. Horn et al., arXiv: 2404.19716

Q-NEXT

Nanocavity-mediated Purcell enhancement of Er in TiO_2 thin films grown via atomic layer deposition

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The use of trivalent erbium (Er^{3+}), typically embedded as an atomic defect in the solid-state, has widespread adoption as a dopant in telecommunications devices and shows promise as a spin-based quantum memory for quantum communication. In particular, its natural telecom C-band optical transition and spin-photon interface makes it an ideal candidate for integration into existing optical fiber networks without the need for quantum frequency conversion. However, successful scaling requires a host material with few intrinsic nuclear spins, compatibility with semiconductor foundry processes, and straightforward integration with silicon photonics. Here, we present Er-doped titanium dioxide (TiO_2) thin film growth on silicon substrates using a foundry-scalable atomic layer deposition process with a wide range of doping control over the Er concentration. Even though the as-grown films are amorphous, after oxygen annealing, they exhibit relatively large crystalline grains, and the embedded Er ions exhibit the characteristic optical emission spectrum from anatase TiO_2. Critically, this growth and annealing process maintains the low surface roughness required for nanophotonic integration. Finally, we interface Er ensembles with high quality factor Si nanophotonic cavities via evanescent coupling and demonstrate a large Purcell enhancement of their optical lifetime. Our findings demonstrate a low-temperature, non-destructive, and substrate-independent process for integrating Er-doped materials with silicon photonics. At high doping densities this platform can enable integrated photonic components such as on-chip amplifiers and lasers, while dilute concentrations can realize single ion quantum memories.

Q-NEXT

Optical Control and Readout of Isotopically Engineered Molecular Color Centers

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Precise control over individual spin qubits and their environments are necessary for elevating quantum technologies to the forefront of computation, sensing, and communication. Molecular electron spins are a powerful candidate for quantum sensing due to their strong coupling to environmental variables, ranging from magnetic and electric fields to temperature. Synthetic chemistry enables the bottom-up design of optically addressable molecular qubits (molecular

color centers) through changing the environment of the electronic spin with atomistic precision. Here, we highlight our chemical control over the isotopic environment of molecular color centers by preparing Cr^{4+} spins in both protonated and deuterated Sn^{4+} hosts and characterizing the spin-optical properties. Our results demonstrate a unique ability to tailor electron-nuclear spin interactions in an optically addressable platform.

Q-NEXT

Room-Temperature Valley-Selective Emission Enabled by Chiral Quasi-Bound States in the Continuum

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Optically addressable spin-photon interfaces in monolayers of transition metal dichalcogenides are pivotal to realizing classical and quantum operations using photons. Valley pseudospin in TMDCs allows circularly polarized light to be coupled with electron (hole) spin, thus enabling initialization and readout of both classical and quantum information. Rapid valley-dephasing processes bottleneck the development of scalable, high-performance valleytronic devices operating at room temperature. Here we demonstrate that a chiral resonant metasurface could enable room-temperature valley-selective emission. This platform, driven by chiral quasi-bound states in the continuum, provides circular eigen-polarization states featuring a high quality factor (Q-factor) and strong chiral near-field enhancement, and results in unitary emission circular dichroism. Our fabricated high-Q-factor (> 200) Si chiral metasurfaces at visible wavelengths strongly enhance valley-selective optical transitions in MoSe2-interfaced devices under linearly polarized light excitation, achieving a high degree of optical circular polarization (DOP) from 100 K to 294 K and reaching nearly 0.5 at 294 K. The high DOP is attributed to favorably enhanced exciton/trion recombination rates at one specific valley. Our work could facilitate the development of compact chiral classical and quantum light sources and the creation of molecular chiral polaritons for quantum enantioselective synthesis.

Q-NEXT

SLAC Superconducting Quantum Foundry

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https://q-next.org/

We will present our efforts in setting up a Quantum Foundry focusing on superconducting devices and sensors, providing for the standardization of processes to address the national need for standardized, robust superconducting quantum devices. The foundry is designed for robust, well-controlled, reproducible fabrication. The SLAC Quantum Foundry provides a suite of metrology kits to standardize processes focused on developing superconducting qubits, continuous-variables quantum sensors, single-photon detectors, and other superconducting quantum devices and sensors. We will describe the commissioning of the full facility, as well as the development of a suite of room temperature metrology and characterization tools and procedures to standardize fabrication. We highlight in-process metrology that is strongly correlated with specific cryogenic testing. The Quantum Foundry will play a role in training a quantum workforce in superconducting devices to meet national needs as well as needs in the Silicon Valley quantum ecosystem.

Q-NEXT

Stroboscopic X-ray diffraction microscopy of dynamic strain in diamond thin-film bulk acoustic resonators for quantum control of nitrogen-vacancy centers

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Bulk-mode acoustic waves in a crystalline material exert lattice strain through the thickness of the sample, which couples to the spin Hamiltonian of defect-based qubits such as the nitrogen-vacancy (NV) center defect in diamond. This mechanism has been previously harnessed for unconventional quantum spin control, spin decoherence protection, and quantum sensing. Bulk-mode acoustic wave devices are also important in the microelectronics industry as microwave filters. A key challenge in both applications is a lack of appropriate operando microscopy tools for quantifying and visualizing gigahertz-frequency dynamic strain. In this work, we directly image acoustic strain within NV center-coupled diamond thin-film bulk acoustic wave resonators using stroboscopic scanning hard X-ray diffraction microscopy at the Advanced Photon Source. The far-field scattering patterns of the nano-focused X-ray diffraction encode strain information entirely through the illuminated thickness of the resonator. These patterns have a real-space spatial variation that is consistent with the bulk strain's expected modal distribution and a momentum-space angular variation from which the strain amplitude can be quantitatively deduced. We also perform optical measurements of strain-driven Rabi precession of the NV center spin ensemble, providing an additional quantitative measurement of the strain amplitude. As a result, we directly measure the six NV spin-stress coupling parameter $b = 2.73(2)$ MHz/GPa by correlating these measurements at the same spatial position and applied microwave power. Our results demonstrate a unique technique for directly imaging AC lattice strain in micromechanical structures and provide a direct measurement of a fundamental constant for the NV center defect spin Hamiltonian.

Q-NEXT

Towards a network of quantum registers with neutral atoms using parabolic mirrors and pre-aligned optics

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We report on progress towards a rudimentary network of quantum registers with neutral atoms. While quantum computing has the potential to out-perform classical computers for certain classes of problems, scaling these platforms to the number of qubits necessary for useful quantum advantage is an outstanding challenge for all architectures. A modular approach based on quantum processors connected by photonic links is one pathway to surmounting this challenge. Here we show experimental progress towards a two-node network of quantum registers using a novel quantum node architecture based on centimeter scale optics in vacuo, which reduces the experimental footprint. Moreover, we demonstrate the first use of a parabolic mirror with neutral atoms, used for trapping of and photon collection from the communication qubits. Memory qubits are held in projected tweezer arrays formed with a passive Fourier filtering technique, where Rydberg gates can be performed both within the memory register and between memory and communication qubits.

Q-NEXT

Towards Quantum Networking: Tin Vacancy in Diamond

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The negatively charged tin-vacancy center in diamond (SnV^-) is an emerging platform for building next-generation long-distance quantum networks due to its favorable optical and spin properties, including bright emission, insensitivity to electronic noise, and long spin coherence times at temperatures above 1 Kelvin. However, for long, it was debatable whether the relatively large ground-state spin-orbit coupling of 830 GHz would prohibit spin control. Here, by use of a naturally strained center, we overcome this limitation and achieve high-fidelity microwave spin control. We demonstrate a π-pulse fidelity of up to 99.51% and a Hahn-echo coherence time of $T_{echo}^2 = 170\ \mu$s, both the highest yet reported for SnV^- platform. Further, we demonstrate a single-shot readout fidelity of 87.4%, which can be further improved to 98.5% by conditioning on multiple readouts. We show that this performance is compatible with rapid microwave spin control, demonstrating that the trade-off between optical readout and spin control inherent to group-IV centers in diamond can be overcome for the SnV^-. Additionally, we use weak quantum measurement to study measurement-induced dephasing, shedding light on the fundamental interplay between measurement and decoherence in quantum mechanics and utilizing the qubit's spin coherence as a metrological tool. These results represent a significant step forward in the development of SnV^- based quantum technologies and contribute techniques and understanding broadly applicable to the study of solid-state quantum emitters.

Q-NEXT

Trilayer Superconducting Qubits Operating at High Temperatures

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Superconducting qubits made with trilayer Josephson junctions are an area of growing interest due to their potential for high temperature and high frequency operation, which is important for applications in sensing and improving scaling considerations. The trilayer fabrication process makes it possible to make junctions using a wide variety of superconducting materials and oxides, including high T_c materials such as niobium, as well as different synthesis techniques, compared with those fabricated through conventional angled evaporation. Using niobium-trilayer-based transmons, we demonstrate a 20 GHz superconducting qubit operating at 200 mK and a 70 GHz superconducting qubit operating at nearly 1 K. We examine these junctions using transmission electron microscopy to uncover potential sources of loss and routes for improvement.

QSA

Advances in Self-Contained Control Hardware

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We present recent progress for a control system that is capable of compiling gate waveforms directly from quantum assembly, where coherent operations can be combined with classical algorithms run on a dual-core real-time processor. This enables tight-loop feedback on gate definitions, as well as fast calibration and advanced optimization techniques, entirely on chip without impacting the experimental duty-cycle. These techniques can be applied to state-of-the-art gates that employ continuously modulated waveforms with non-trivial parametrization, while maintaining the ability to schedule numerous circuits comprising millions of unique gates. Moreover, our master-free design approach, robustness to timing jitter, and flexible support for off-chip communication, enables extensible operation for a wide variety of applications.

QSA

Detection and cooling of atoms without destroying the encoded quantum information

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Optically trapped atoms in arrays of optical tweezers have emerged as a powerful platform for quantum information processing given the recent demonstrations of high-fidelity quantum logic

gates and on-demand reconfigurable geometry. Both in gate operations and in atomic transport, additional errors will occur due to leakage out of the computation space, atomic motional heating, or loss of an atom out of a trap completely. In this work, we address these error channels in a unified manner through laser fluorescence that can detect and cool the atom without disturbing the quantum information encoded therein. As only the electrons in the atom couple directly to the laser field, such quantum non-demolition (QND) processes are made possible by encoding quantum information in the nuclear spin of alkaline earth-like and avoiding effects of the hyperfine interaction which couples it to the electrons. We first show this can be achieved by driving the imaging transition far-off resonantly and cancelling resulting lightshifts. We also show that this can be achieved by disabling the Hyperfine interaction in the 1P1 manifold by using strong lightshifts. The latter method can also be used to sideband cool the atoms without destroying the encoded quantum information. These advances could significantly improve the prospects for fault-tolerance computations with neutral atoms.

QSA

Macrostates vs. Microstates in the Classical Simulation of Critical Phenomena in Quench Dynamics of 1D Ising Models

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In nonequilibrium dynamics, a common objective is estimating a dynamical order parameter, specified by the expectation value of local (few-body) observables. While accurate calculation of the full many-body state (microstate) is typically intractable due to the volume-law growth of entanglement, when simulating phases of matter associated with the macro-properties of many-body systems, a precise specification of an exact microstate is rarely required. We study critical phenomena in the quench dynamics of one-dimensional (1D) Ising models using truncated Matrix Product States (MPS). Here we simulate the critical behavior of a Z2 symmetry breaking dynamical quantum phase transition (DQPT) for a nonintegrable transverse field Ising model with long-range interactions. For the DQPT, we show that the order parameters, critical point and critical exponents can be efficiently simulated with heavy truncation of the MPS bond dimension. We also estimate long-time correlation lengths of the integrable 1D nearest-neighbor transverse field Ising model, finding that such properties that depend on the exact microstate can also be efficiently simulated because they can be extracted from the short duration behavior of the dynamics. The tractability of simulation using truncated MPS is explained based on quantum chaos and equilibration in the model. Our results provide illustrations of scenarios where accurate calculation of the full many-body state (microstate) is intractable due to volume-law growth of entanglement, yet a precise specification of an exact microstate may not be required when simulating macro-properties that play a role in phases of matter of many-body systems.

QSA

Noise induced regression to classical dynamics in the single mode Kerr effect

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http://www.NQISRC.com

Quantum information processing devices promise speed-ups in certain tasks over their classical counterparts, especially as the system size grows. However, it is well known from the seminal work of Zurek and others that a quantum system undergoing decoherence regresses to its classical counterpart as time progresses, and does so more rapidly as the system becomes more macroscopic. Progress in the Noisy Intermediate Scale Quantum (NISQ) computing era motivates us to better understand this transition in a quantitative way. In this study, we quantify the quantum-to-classical transition of single mode Kerr Hamiltonian in the presence of noise. We study the interplay of generation of coherence and the degradation of this coherence with the increasing system size. It is shown that, as we increase the system size, the generation of so-called kitten states is severely restricted even in the presence of modest photon-loss. We show that the expectation values of observables coincide with the classical expectation values in this regime. Given that the generation of kitten states is severely restricted, we further ask, is there any "quantumness" generated in the system at early times by studying the early time behavior based on a mean-field approximation. Our results quantify the effect of noise on the quantum resources generated in the system and cast doubt on the effectiveness of NISQ devices.

QSA

Observation of a Finite-Energy Phase Transition in a One-Dimensional Quantum Simulator

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One of the most striking many-body phenomena in nature is the sudden change of macroscopic properties as the temperature or energy reaches a critical value. Such equilibrium transitions have been predicted and observed in two and three spatial dimensions, but have long been thought not to exist in one-dimensional (1D) systems. Fifty years ago, Dyson and Thouless pointed out that a phase transition in 1D can occur in the presence of long-range interactions, but an experimental realization has so far not been achieved due to the requirement to both prepare equilibrium states and realize sufficiently long-range interactions. Here we report on the first experimental demonstration of a finite-energy phase transition in 1D. We use the simple observation that finite-energy states can be prepared by time-evolving product initial states and letting them thermalize under the dynamics of a many-body Hamiltonian. By preparing initial states with different energies in a 1D trapped-ion quantum simulator, we study the finite-energy phase diagram of a long-range

interacting quantum system. We observe a ferromagnetic equilibrium phase transition as well as a crossover from a low-energy polarized paramagnet to a high-energy unpolarized paramagnet in a system of up to 23 spins, in excellent agreement with numerical simulations. Our work demonstrates the ability of quantum simulators to realize and study previously inaccessible phases at finite energy density.

QSA

Optical Tweezer Arrays of Ultracold Molecules

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Polar molecules combine rich internal structures with large electric dipole moments, making them an appealing resource for quantum simulation and quantum information processing applications. In an ultracold molecular platform, quantum information is stored in the many vibrational, rotational, and/or hyperfine states of each polar molecule, while molecules in an array are entangled using strong, long-range, and anisotropic dipolar interactions. Though the complexity of polar molecules makes them challenging to cool and control at the single quantum state level, tremendous progress has been made over the last 10-15 years, and we are now at a point where arrays of individual diatomic – and very recently triatomic – molecules can be created and manipulated. Here, we discuss our work with optical tweezer arrays of the laser-cooled polar molecules CaF and CaOH. Key results to be presented include the demonstration of long coherence times and dipolar-interaction-mediated entanglement between ultracold CaF molecules in an optical tweezer array. We also discuss our work cooling CaF molecules to the motional ground state of the optical tweezers. Shifting our focus to polyatomic molecules, which have complex structure that is uniquely suited to certain quantum science applications, we demonstrate the creation of an optical tweezer array of CaOH molecules with direct molecular imaging and quantum state control capabilities. Finally, we present a novel laser cooling technique for molecules – "conveyor belt trapping" – that is expected to enable the formation of even larger optical arrays of molecules in future work.

QSA

Quantum Coarsening and Collective Dynamics on a Programmable Quantum Simulator

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Understanding the collective quantum dynamics of nonequilibrium many-body systems is an outstanding challenge in quantum science. In particular, dynamics driven by quantum fluctuations are important for the formation of exotic quantum phases of matter, fundamental high-energy processes, quantum metrology, and quantum algorithms. Here, we use a programmable quantum simulator based on Rydberg atom arrays to experimentally study collective dynamics across a (2+1)D Ising quantum phase transition.

After crossing the quantum critical point, we observe a gradual growth of correlations through coarsening of antiferromagnetically ordered domains. By deterministically preparing and following the evolution of ordered domains, we show that the coarsening is driven by the curvature of domain boundaries and find that the dynamics accelerate with proximity to the quantum critical point. We quantitatively explore these phenomena and further observe long-lived oscillations of the order parameter, corresponding to an amplitude (Higgs) mode. These observations offer a unique viewpoint into emergent collective dynamics in strongly correlated quantum systems and nonequilibrium quantum processes.

QSA

Quantum metrology and simulation with matter-waves in a high-finesse cavity

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In quantum simulation and condensed matter physics, interactions are traditionally limited to pairwise, or 2-body, interactions. However, there is a growing interest in exploring more complex n-body interactions (n > 2), which hold promise for implementing efficient quantum gates, simulating exotic many-body states, and generating entanglement with high-order correlations. In this work, we experimentally realize the mean-field dynamics of a 3-body Hamiltonian interaction using an ensemble of laser-cooled rubidium atoms within a high-finesse optical cavity. By encoding pseudo-spin 1/2 in atomic momentum states and applying two dressing laser tones, we induce a resonant six-photon process where lower-order interactions destructively interfere, resulting in only the 3-body interaction. We can extend this to a 4-body interaction mediated by an eight-photon process which we also observe. Our approach provides a novel platform for quantum simulation of systems with high-order correlations, potentially paving the way for new entangled states in quantum sensing, novel phases in self-organization, and robust quantum error correction codes. The experimental setup and results demonstrate the feasibility of using momentum states, rather than spin states, to explore complex quantum systems and enhance quantum information processing.

QSA

Quantum Metrology with Alkaline-Earth Atom Arrays

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Programmable arrays of alkaline-earth atoms have emerged as a versatile experimental platform for quantum science. Together with Rydberg interactions, control at the single-particle level makes such atom arrays ideal systems for studying how quantum entanglement can be harnessed to improve atomic-clock performance. In our experiment, we achieve this goal by engineering Rydberg interactions for the preparation of different entangled states with metrological gain.

QSA

Quantum Simulation of Spin-Boson Models with Structured Bath

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The spin-boson model, involving spins interacting with a bath of quantum harmonic oscillators, is a widely used representation of open quantum systems that describe many dissipative processes in physical, chemical and biological systems. Trapped ions present an ideal platform for simulating the quantum dynamics of such models, by accessing both the high-quality internal qubit states and the motional modes of the ions for spins and bosons, respectively. We demonstrate a fully programmable method to simulate dissipative dynamics of spin-boson models using a chain of trapped ions, where the initial temperature and the noise spectral densities of the boson bath are engineered by controlling the state of the motional modes and their coupling with qubit states. Our method provides a versatile and precise experimental tool for studying open quantum systems.

QSA

Quantum Simulations of High Energy Physics At Large N

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Quantum computers are anticipated to enable simulations of the dynamics of strongly coupled theories such as Quantum Chromodynamics. These simulations will enable new theoretical predictions to be performed. In particular, quantum simulations will allow us to directly simulate the non-perturbative aspects of jet fragmentation and hadronization. In this work, we combined a large N expansion with the Hamiltonian formalism of lattice QCD. This leads to a dramatic simplification in the encoding of gauge fields onto a quantum computer and the construction of the time evolution operator. This simplified mapping was used to simulate the dynamics of a SU(3) lattice gauge theory on an 8x8 lattice using one of IBM's quantum computers. The Hamiltonian of this truncation of QCD is the same as some neutral atom experiments which will enable near term analog simulations of the dynamics of the gauge fields of QCD

QSA

Simulating Meson Scattering on Spin Quantum Simulators

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Studying high-energy collisions of composite particles, such as hadrons and nuclei, is an outstanding goal for quantum simulators. However, the preparation of hadronic wave packets has posed a significant challenge, due to the complexity of hadrons and the precise structure of wave packets. This has limited demonstrations of hadron scattering on quantum simulators to date. Observations of confinement and composite excitations in quantum spin systems have opened up the possibility to explore scattering dynamics in spin models. In this article, we develop two methods to create entangled spin states corresponding to wave packets of composite particles in analog quantum simulators of Ising spin Hamiltonians. One wave-packet preparation method uses the blockade effect enabled by beyond-nearest-neighbor Ising spin interactions. The other method utilizes a quantum-bus-mediated exchange, such as the native spin-phonon coupling in trapped-ion arrays. With a focus on trapped-ion simulators, we numerically benchmark both methods and show that high-fidelity wave packets can be achieved in near-term experiments. We numerically study the scattering of wave packets for experimentally realizable parameters in the Ising model and find inelastic-scattering regimes, corresponding to particle production in the scattering event, with prominent and distinct experimental signals. Our proposal, therefore, demonstrates the potential of observing inelastic scattering in near-term quantum simulators.

QSA

Site-selective cavity readout and classical error correction of a 10-bit atomic register

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Optical cavities have been used for the fast and non-destructive readout of hyperfine states of individual atomic qubits, however scaling up to many qubits remains a challenge. Using an optical cavity, we realize site-selective sequential readout of the hyperfine states of a 10-atom array with locally addressed excited state Stark shifts. The state discrimination fidelity is 0.994(1) for one atom and 0.989(2) averaged over the entire array, and the state-averaged survival probability is 0.975(1). For future applications such as scalable syndrome readout, we implement adaptive search strategies utilizing global/subset checks. Finally, we demonstrate repeated rounds of classical error correction showing exponential suppression of logical error and extending logical memory five-fold beyond the single-bit idling lifetime.

QSA

Tailoring Molecular Clusters with Quantum Computers

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Electronic excitation of molecular clusters are the microscopic dynamics governing the efficacy of both photovoltaic cells and photosynthetic reaction centers, as well as those emerging technologies that lie in between. In most cases, accurately capturing the behavior of such systems requires understanding not only changes to the electrons within them, but also the changes to molecular vibration. Simulating the dynamics of such a complex and interconnected system is a prime application of quantum computers. In this work, we experimentally simulate the transfer of an electronic excitation along a chain of macromolecules under a variety of conditions using a trapped-ion-based quantum computer. Our approach begins by using the relatively accessible spectroscopic data of an isolated macromolecule, pseudoisocyanine, as the input to a hybrid quantum-classical optimization algorithm which creates a digitally prepared wavefunction describing that macromolecule. Thereafter, we use an ab initio model to track the dynamics of a cluster of three macromolecules. We perform these simulations for a variety of different inter-molecular couplings by varying the relative angle between the molecules in the cluster, providing proof of principle for ab-initio design of molecular clusters with tailored excitation transfer rates. On a scaled up quantum computer, these methods could be used to design chemically assembled highly efficient organic solar cells.

QSA

The Zeno Effect: A Versatile Tool for Quantum Control & Computation

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The quantum Zeno effect is typically described in terms of a measurement freezing a quantum system's dynamics. We here consider instead measurement-driven "Zeno dragging" control of the system's dynamics, implemented by an evolving measurement or dissipator. We illustrate how optimal measurement-driven control can be derived in the context of continuous measurements, and describe how this leads to dissipatively-protected quantum operations. Then we demonstrate how multi-measurement Zeno dragging can be used to realize measurement-driven quantum computation. Specifically, we emphasize an algorithm for solving Boolean satisfiability problems (k-SAT) using generalized quantum measurements.

QSA

Towards Dipolar Quantum Magnetism with Ytterbium Rydberg Atom Arrays

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Quantum many-body systems with dipolar interactions host a variety of exotic phases of matter, such as quantum spin liquids. To study this physics in the lab, dipolar interactions have been realized in various systems including polar molecules, magnetic atoms and alkali Rydberg atoms. However, to fully explore the phases of dipolar Hamiltonians, it is necessary to scale up to larger system sizes, minimize positional disorder, and prolong the coherence time. Here we present a new dipolar Yb tweezer apparatus designed to address these challenges. By trapping Yb atoms excited to Rydberg states and using microwaves to couple opposite parity states, we will study the dipolar XY on frustrated lattice geometries. Our apparatus features a large field-of-view objective and in-vacuum electrodes, which are crucial for realizing system sizes of up to a thousand atoms and careful control of the interactions, respectively. This work paves the way towards studying new phases such as dipolar supersolids and chiral spin liquids.

QSC

Completion of the Quantum Underground Instrumentation Experimental Testbed (QUIET)

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http://www.qscience.org/

The requirements from quantum computing to isolate a quantum state from its environment for long enough to perform error-free calculations requires mitigation and modeling of information loss mechanisms. One such loss mechanism is from radiation, such as from cosmic rays or natural radioactivity, interacting with the system near the qubit. 100 meters underground at Fermilab, using techniques originally developed in particle physics for dark matter direct detection, the Quantum Science Center (QSC) has completed construction and commissioning of the Quantum Underground Instrumentation Experimental Testbed (QUIET), one of the first dedicated, underground Quantum Information Science (QIS) facilities in the United States. First devices will be deployed in this unique environment for the first time over the next months, with results expected early next year.

QSC

Designing Materials to Enhance Topological Superconductivity for Quantum Computing Applications

Robert G. Moore[1]

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We explore the creation of topological superconducting platforms that support Majorana bound states, which hold promise for revolutionizing quantum computing. Achieving these states by interfacing a s-wave superconductor with a topological insulator requires precise and simultaneous control over superconductivity and spin-momentum locked topological states. Here, we present our advancements in enhancing material properties while reducing disorder, alongside fabrication methods for creating devices using proximitized materials. Additionally, we introduce new nonlocal transport techniques for more reliable interrogation of Majorana modes. These co-designed approaches open new avenues for scientific discovery and the development of quantum computing and sensing technologies.

QSC

Estimating the Energy Threshold of Qubit-based Detectors in a Relaxation Sensing Scheme

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Over the last decade, several low-energy physics searches, including the hunt for particle dark matter, have driven interest in developing increasingly sensitive particle detectors. Superconducting quantum sensors based on Cooper Pairs provide a possible channel for sensing O(meV) energy depositions, and therefore could represent a significant step in developing such low-threshold detectors. In this poster we present a bottom-up estimate of the energy threshold of a superconducting qubit operated in an energy-relaxation sensing scheme. We model the in-substrate phonon response with the G4CMP low-energy physics simulation package and model the evolution of phonon-created quasiparticles and qubit state with a custom package called QDR (Quantum Device Response). Using a novel energy reconstruction technique for qubits operated in this sensing scheme, we estimate an in-qubit energy threshold for near-term devices of approximately 0.4 eV. Moreover, we confirm the validity of this technique by applying it to recently published data in which cosmic rays were observed to pass through a qubit chip.

QSC

Experimental Evaluation of Quantum Spin Liquids Using Protocols

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The identification of quantum spin liquid materials is a challenging task, yet it is vital for the development of magnetic based quantum information technologies. A principal problem is the lack of single, unambiguous measurements that can uniquely identify the topological quantum states involved without the costly and technically difficult step of creating quantum interferometers with the materials in question. To address this urgent need we have developed a protocol that uses innovations in quantum measurement theory, Hamiltonian determination with neutrons, and validation against theoretical predictions to down-select materials. This involved demonstrating the extraction of quantum entanglement witnesses from neutron scattering data that quantify the degree of entanglement of the spins in the material with the rest of the spins in the network as well as the entanglement depth of this network. We also used a novel approach of applying high magnetic fields to make the materials behave more classically in order extract the actual couplings between spins by measuring the magnetic dynamics in such states. Finally, advances in the application of quantum simulations on classical computers allow our neutron spectra to be compared to spin liquid predictions. Our results, and the application of the protocol, are illustrated on triangular quantum spin liquid candidates.

QSC

First Measurement of Correlated Charge Noise in Superconducting Qubits at an Underground Facility

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https://www.qscience.org

Recent work indicates that non-equilibrium quasiparticles can contribute to decoherence effects in superconducting qubits. Ionizing radiation, for example, has been shown to create errors in qubit arrays that are correlated in both space and time. For quantum computing, such correlated errors create problems for standard error-correcting codes. For quantum sensing, these same phenomena can represent a possible measurement channel (sensing particle interactions in the qubit substrate) or a possible background (increasing quasiparticle-induced decoherence). We present results from measurements of an array of weakly charge-sensitive superconducting qubits exposed to a range of radiation fluxes. These experiments were done at the NEXUS low-background test stand 100 meters (225 m.w.e.) underground at Fermilab's MINOS experimental area, allowing for greater control over radiation fluxes than is typically available in above-ground lab environments. We present recent results on the correlations between radiation flux and the stability of qubit gate charge, as well as the implications of these observations for future qubit-based dark matter experiments.

QSC

Leveraging Genetic Strategies and Hybrid Classical-Quantum Computing for Quantum Circuit Design

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[1]Oak Ridge National Laboratory

https://code.ornl.gov/gonzalo_3/evendim

Quantum computing could advance basic science with software that automatically generates quantum circuits to compute the ground state of a given Hamiltonian. Our free and open-source software development already accomplishes this, but it is not yet efficient. This poster will discuss the roadmap to achieve efficiency and the potential roadblocks. To make this work, we need to penalize or discard deep layered circuits, and we will examine the impact on convergence. The need for high-performance (classical) computing and the benefits of hybrid computing, where quantum circuit fitness can be evaluated on quantum hardware, will also be addressed. We are adapting this methodology and developing software to execute our algorithm on large scale HPC cluster including the Summit supercomputer at ORNL, utilizing XACC with various accelerators. This strategy can be extended to solving combinatorial problems using quantum computers. Fields such as condensed matter, computational chemistry, and high-energy physics should benefit from this approach, as our generator provides insightful, non-intuitive quantum circuits that could not have been designed manually.

QSC

In-situ ARPES Study on magnetic-topological-superconducting Heterostructures and Direct Observation of an Interfacial Topological Superconducting States

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Topological superconductivity (TSC) has been proposed as an ideal platform to achieve error-correction quantum computers, as it could host Majorana zero modes. The Majorana zero mode could be hosted in the vortex of a topological superconductor which hosts the electronic states that contain topological and superconducting orders. On the other hand, Skyrmion, a magnetic topological local texture, has been observed at the interface between ferromagnetic and topological insulating interface. Further, the interaction between Skyrmion and Majorana states could lead a new way to achieve Majorana Braiding. Here, we use molecular beam epitaxy (MBE) to build magnetic-topological-superconducting heterostructures, high-quality monolayer $FeTe_{0.8}Se_{0.2}$ on Bi_2Te_3 thin film on $CrTe_2$ thin film, where the topological superconducting surface states is formed at the interface between $FeTe_{0.8}Se_{0.2}$ on Bi_2Te_3 and the Skymion bubble is formed at the interface between Bi_2Te_3 and $CrTe_2$ thin film. We further used spin and angle resolved photoemission spectroscopy (SpinARPES) to direct observe the interfacial topological superconducting states, where coexists with ferromagnetic order. This platform can be an ideal model to study Majorana states and its interaction with magnetic order.

QSC

NWQSim: An Integrated Quantum System Simulation Package

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https://github.com/pnnl/NWQ-Sim

Despite recent achievements in NISQ devices, numerical simulation of quantum systems via classical HPC is still essential in validating quantum algorithms, learning noise effects, and designing new quantum devices. The PNNL-led software team under QSC Software Thrust developed NWQSim, a simulation environment for functional and noisy simulation of quantum circuits and devices, through state-vector and density-matrix representations, on DOE leadership computing facility (LCF) systems, such as Frontier, Summit, and Perlmutter. It supports CPU/GPU backends, with TensorCore/MatrixCore/AVX512 acceleration, and communicates via NVSHMEM/ROCSHMEM/MPI. It performs 42-qubit simulation on 4,096 A100 GPUs on NERSC Perlmutter and scales out to 16,384 V100 GPUs on SummitPLUS.

QSC

Photonic Quantum Computing and Sensing at the QSC

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https://www.qscience.org

Photonic quantum systems offer unique capabilities for quantum computing and quantum sensing due to the degree of control that they offer, and the number of systems and devices light can interface with. Here, we describe some of the ongoing work at the Quantum Science Center (QSC) on the development of a continuous variable (CV) photonic quantum platform for quantum computing and sensing. In particular, we show its capabilities through the implementation of a CV quantum compiler to characterize the parameters of an unknow unitary with quantum-enhanced speed and precision, the development of quantum-enhanced optomechanical sensors for dark matter detection, and the use of entangled states of light for quantum-enhanced characterization of quantum materials.

QSC

QICK-in-a-box. The Quantum Instrumentation Control Kit for QIS

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https://github.com/openquantumhardware/qick

The Quantum Instrumentation Control Kit (QICK) is a standalone, high performance, open-source controller for Quantum Information Science (QIS). QICK has a fast-growing community of over 350 users at DOE-NQI labs, academia, and industry with users across Americas, Europe, and Asia. QICK is used to control superconducting, spin and cold-atom (AMO) qubits as well as a tool for quantum networking and quantum sensors. QICK for quantum sensing has been applied to dark matter and dark energy searches. QICK principal characteristics are, high level functionality, flexibility, and scalability, open source, and low cost.
QICK achieves high-fidelity qubit control and multiplexed readout with advanced RF engineering and digital signal processing. It controls superconducting qubits from DC to 10 GHz frequency spectrum. Multi-channel control and readout are time synchronized to a master clock in firmware. The built-in Linux and logic processors on the FPGA accelerate the execution of multi-qubit complex quantum algorithms. QICK provides low-latency conditional logic required for feedback and feedforward control. The system is highly parallel, multiple QICK boxes can be aggregated to make a fully synchronous system, communicated with 100ns message passing.
QICK allows unique functionality to quantum experiments that require, no analog mixers, sub-ns fast flux pulses, phase-coherent pulses for parametric operations, including high-fidelity parametric entangling gates. For AMO qubits, provides multi-thousand atom tweezers. For spin qubits it provides pico-second time tagging and feedback control.
A low-cost QICK platform with a qubit emulator is available for education and has been used in the annual DOE-NQI schools and conferences.

QSC

Oqtant; a neutral atom quantum matter testbed and service for all

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http://oqtant.infleqtion.com

The Oqtant platform provides remote access to ultracold atoms and quantum matter, in the form of a Bose-Einstein Condensate of rubidium atoms, over the cloud. Many of the capabilities of Oqtant have been developed in partnership with QSC researchers at LANL in order to directly support their research goals as well as provide this service to the wider quantum, and quantum curious, communities. Using Oqtant, users can control the creation, and then manipulation, of quantum matter using either a basic web interface or more capable python API with high-level abstractions. Oqtant allows educators to bring quantum phenomena and real experimental data into the classroom, research scientists without access to an expensive laboratory to do research with quantum matter, members of the public who are curious about quantum phenomena a place to engage, and industry partners a starting point for understanding what quantum can do for them. Currently, the platform supports manipulation of quantum matter with blue-detuned "painted" light projected on the atoms, which facilitates near-arbitrary and dynamic potential-energy surfaces to be applied. This functionality serves as a starting point for studying quantum interference, tunneling, sound, solitons, shockwaves and vortices, continuous quantum algorithms, atomtronics, quantum sensing / interferometry, and more.

QSC

Quantum Enhanced Impulse Measurements with Mechanical Sensors in the Search for Dark Matter

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https://www.qscience.org

Recent advances in mechanical sensing technologies have led to the suggestion that heavy dark matter candidates around the Planck mass range could be detected through their gravitational interaction alone. With this ultimate goal on the horizon, the Windchime collaboration is involved in developing the necessary techniques, systems, and experimental apparatus using arrays of optomechanical sensors. These can also be used to investigate non-gravitational signals from other dark matter candidates in the near-term. However, to achieve Planck-scale detection, measurements of these devices will need to go beyond the standard quantum limit. Hence, we need to employ quantum-enhanced readout techniques for detecting the extremely weak impulses due to the gravitational interaction of dark matter. Here we discuss the different techniques for achieving such quantum-enhanced measurements in optical and microwave domain, which would help us in reducing the measurement-added noise floor in experimentally relevant parameter regimes in order to reach our desired sensitivity.

QSC

Quantum phases of Rydberg atoms on Shastry - Sutherland lattice

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We explore the phase diagram of Rydberg atoms in a frustrated Shastry-Sutherland lattice. Using the density matrix renormalization group, we map out a rich phase diagram in a three-dimensional parameter space that is naturally realizable in current Rydberg atom platforms. In particular, besides a plethora of classical phases, we show the presence of phases stabilized exclusively by quantum fluctuations. We employ order parameter symmetry analysis to show the presence of novel quantum critical points. Lastly, we tested most of the theoretical predictions experimentally using QuEra's Rydberg atom array quantum simulator and found excellent agreement between theoretical predictions and experiments.

QSC

Quantum Simulations of the Schwinger Model: State Preparation and Time Evolution using 100+ Qubits

Roland C. Farrell[1], Marc Illa[1], Anthony N. Ciavarella[1,2], and Martin J. Savage[1]

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https://www.qscience.org

Quantum electrodynamics in 1+1 dimensions (the Schwinger model) exhibits a number of features similar to quantum chromodynamics in 3+1D, including confinement and a fermion condensate, making it the perfect sandbox during the NISQ era. In this poster, I will present new scalable algorithms that use the symmetries and hierarchy of length scales in the Schwinger model (and generally applicable to other confining theories) for state preparation and simulating the real-time dynamics of hadrons on a quantum computer, and their realization on a 56-site lattice (112 qubits) using IBM's quantum computers.

QSC

Simulating Superconducting Devices in Novel Materials Using the G4CMP Simulation Toolkit

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Understanding the kinematics of phonons and charge propagation in superconducting devices is crucial for conducting low-threshold dark matter searches and minimizing correlated errors in superconducting qubits. For nearly a decade, the Geant4 Condensed Matter Physics (G4CMP) package, originally developed for the Cryogenic Dark Matter Search (CDMS) experiment, has been limited to simulating charge and phonon transport in silicon and germanium materials. In this work, we have expanded the capabilities of G4CMP to include novel substrate materials such as sapphire (Al_2O_3), Gallium Arsenide (GaAs), Lithium Fluoride (LiF), Calcium Tungstate ($CaWO_4$),

and Calcium Fluoride (CaF2). We demonstrate the use of this toolkit in generating phonon transport properties for these materials and compare the results with experimentally determined values where available. Additionally, we explore the performance of superconducting devices utilizing these materials.

QSC

Topological insulator/superconductor hybrid devices: from Josephson junctions to antidots

Yong Chen[1]

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Topological insulator(TI)/superconductor(S) hybrid systems are proposed as promising platforms to realize topological superconductivity (TSC), majorana fermions and majarana zero modes (MZM), with potential applications in topologically protected quantum information. This poster will review the recent progress by our team and QSC project in experimental studies (using various techniques ranging from dc and ac transport and scanning tunneling microscopy) and associated modelling of such TI/S materials and hybrid devices, particularly S/TI/S Josephson junctions and TI/S "antidots" (designed to trap majoranas). The work paves the way toward further manipulation and characterizations of this candidate TSC/majorana systems, ultimately to demonstrate the interaction and fusion of MZMs to establish their non-Abelian anyon nature.

QSC

TRSB and Axions in Topological Quantum Matter

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http://www.NQISRC.com

Here we present the use of circuit quantum electrodynamics (circuit QED) to probe time-reversal symmetry breaking in topological quantum matter, including those that host axionic quasiparticles. The unusual magnetoelectric transport present in topological Weyl semimetals and 3D topological insulators can be compactly understood as manifestations of a background axion field, which itself is determined by the microscopic band structure.
In the presence of correlations, an additional axion quasiparticle may emerge as the collective excitations on top of the mean background field. However, unambiguous identification of this collective axion mode is challenging due to its inherent nonlinear dynamics. We present recent work on axion detection techniques in topological quantum matter. The first is an all-optical detection protocol that utilizes a pump-probe setup for verifying and characterizing the transient dynamics of axion fields in three-dimensional insulator systems, with an optical signature manifesting in the time-dependent Kerr rotation. The second detection technique relies on use of a cQED platform designed to identify time-reversal symmetry breaking, where the dynamics of the

axion are embedded in the quantum metric. I will show how the electromagnetic properties of the material are encoded in the dynamics of the photonic states and formulate a measuring protocol that can be used to sensitively measure small nonreciprocal responses in the material, e.g., through magnetic or chiral topological order. Our process tomography method utilizes the quantum geometry of photonic wavefunctions, and represents a concrete application of quantum metrology across a broad spectrum of experimental platforms.

SQMS

Cavity-Based Microwave Characterization for Calculating Losses in Superconducting Qubits

Daniel Bafia[1], Bektur Abdisatarov[1,2], Anna Grassellino[1], Akshay Murthy[2], and Alexander Romanenko[1]

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https://sqmscenter.fnal.gov/

To enable the next generation of superconducting quantum devices, it is necessary to identify every radiofrequency (RF) loss subcomponent in our present-day qubits and develop mitigation strategies to minimize quantum decoherence. The record quality factors achievable in niobium superconducting radiofrequency (SRF) cavities enable RF dissipation measurements for a variety of materials with parts per billion precision at the low electric fields and mK temperatures relevant for superconducting quantum computing architectures. These resonators serve as a simplified single-interface system which allow for direct measurement of the losses in the material from which the cavity itself is made. Moreover, these structures are used as sample hosts to test a variety of dielectric materials. By coupling these RF measurements with materials science techniques, such as time-of-flight secondary ion mass spectrometry and x-ray photoelectron spectroscopy, we identify material sources of loss which drive quantum decoherence in oxides and substrates typically used in the fabrication of qubits.

C-STEEL established a baseline standard and benchmark to coordinate research efforts across institutions. We will present our recent results comparing iron electrodeposition to H_2 evolution in aqueous solutions as a function of iron solvation structures and assess the effects of air oxidation, concentration, and anion species. Future efforts will be guided by (and will expand) C-STEEL's trustworthy AI model that accurately predicts the redox potentials of Fe-complexes. Additionally, recent advances in large scale sampling of machine learning interatomic potentials (MLIPs) and determining the Fe(II) activity in multivalent salt systems will be discussed. Based on these results, we'll establish strategies to enable electrolyte design for enhance efficiency and current density of iron plating.

SQMS

Disentangling the Impacts of Quasiparticle and Two-Level System on the Statistics of the Superconducting Qubit Lifetime

Shaojiang Zhu,[1] Xinyuan You,[1] Ugur Alyanak,[1, 2] Mustafa Bal,[1] Francesco Crisa,[1] Sabrina Garattoni,[1] Andrei Lunin,[1] Roman Pilipenko,[1] Akshay Murthy[1], Alexander Romanenko,[1] and Anna Grassellino[1]

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Temporal fluctuations of the superconducting qubits lifetime, T_1, bring up additional challenges in building a fault-tolerant quantum computer. While the exact mechanisms remain unclear, T_1 fluctuations are generally attributed to the strong coupling between the qubit and a few near-resonant two-level systems (TLSs) that can exchange energy with an assemble of thermally fluctuating two-level fluctuators (TLFs) at low frequencies. Here, we report T_1 measurements on the qubits with different geometrical footprints and surface dielectrics, as a function of the temperature. By analyzing the noise spectrum of the qubit depolarization rate, $\Gamma_1 = 1/T_1$, we can disentangle the impacts of TLSs, non-equilibrium quasiparticles (QPs), and equilibrium (thermally excited) QPs on the Γ_1 variance. We find that, compared to those in the large-footprint qubits, Γ_1 variances in the qubit with small footprint are more susceptible to the QP and TLS fluctuations. Furthermore, the QP-induced variances in all qubits are consistent with the theoretical framework of QP diffusion and fluctuation. We suggest that these findings can offer valuable insights for future optimizations of the qubit design and engineering.

SQMS

Evaluating Radiation Impact on Superconducting Transmon Qubits in Above and Underground Facilities

Tanay Roy[1], Francesco De Dominicis[2,3], Ambra Mariani[4], Mustafa Bal[1], Nicola Casali[4], Ivan Colantoni[4], Francesco Crisa[5], Angelo Cruciani[4], Fernando Ferroni[2,4], Dounia L Helis[3], Lorenzo Pagnanini[2,3], Valerio Pettinacci[4], Roman Pilipenko[1], Stefano Pirro[3], Andrei Puiu[3], Alexander Romanenko[1], Marco Vignati[4,6], David v Zanten[1], Shaojiang Zhu[1], Anna Grassellino[1], and Laura Cardani[4]

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Superconducting qubits can be sensitive to sudden energy deposits into the substrate from cosmic rays and ambient radioactivity. While previous studies have primarily focused on exploring correlated effects over time and distance due to cosmic rays, this study uniquely offers a direct comparison of a transmon qubit's response at Fermilab SQMS above-ground facilities and the deep-underground Gran Sasso Laboratory (INFN-LNGS, Italy). Despite the vastly different radiation environments, we observe a similar average qubit lifetime (T1) of approximately 80 microseconds at both sites. We then employ a fast decay detection protocol and investigate the time structure, sensitivity, and relative rates of triggered events due to radiation versus intrinsic noise. We compare the above and underground performance of several high-coherence qubits with similar

designs. Our findings reveal no significant difference in events with radiation-like signatures between above-ground and underground conditions for these sapphire and niobium-based transmon qubits. This suggests that most such events are likely due to other noise sources, which predominantly contribute to single-qubit errors in contemporary transmon qubits. By exposing the qubits to gamma sources with varying activity levels, we further evaluate their response to radiation in a low-background environment. The results show that qubits can indeed detect particle impacts; however, this capability is only realized by substantially reducing other noise sources, which in turn affects detection efficiency [1].
[1]: Dominicis and Roy et al. arxiv:2405.18355

SQMS

Material and Interface Engineering Strategies to Mitigate Decoherence in Superconducting Qubits

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While significant strides have been made to increase the coherence time of superconducting qubits, further advancements are essential for realizing scalable quantum computing. Decoherence is often a result of loss and noise stemming from two-level systems and excess quasiparticles, arising due to material defects, fabrication processes, and ambient exposure, particularly at surfaces and interfaces. Our recent efforts to mitigate these decoherence mechanisms have employed a variety of strategies, including low-loss surface encapsulation materials, advanced substrate preparation techniques, modifications to metal film growth, and the development of novel fabrication processes. The structural and chemical properties of materials, surfaces, and interfaces are studied using scanning probe microscopy, electron microscopy, photoelectron spectroscopy, mass spectrometry, and X-ray diffraction, which is correlated to device performance metrics, including superconducting resonator internal quality factor and qubit T1 time. This information is used to identify and understand material sources of loss and their origins in the device fabrication process. Through multi-institution efforts within SQMS we have identified the loss mechanism of interstitial hydrogen in niobium-based devices and shown how standard fabrication processes introduce these hydrides, developing strategies to mitigate their formation.[1] Furthermore, we have characterized the metal-substrate interface, including the loss of niobium-silicides formed at that interface, and developed silicon surface treatments that reduce atomic scale roughness and oxygen content at the metal-substrate and Josephson junction interfaces.[2-4] By developing the connection between materials' properties and the overall performance of superconducting quantum circuitry, we can develop fabrication strategies to mitigate material losses, thus supporting the ongoing efforts to enhance coherence time in superconducting quantum devices.

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SQMS

Progress on 3D SRF-based architecture for quantum computing

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Superconducting radio frequency (SRF) cavities are excellent choices for storing and manipulating quantum information as quantum d-level systems (qudits) due to their exceptionally long lifetimes and large accessible Hilbert spaces. A common strategy to manipulate the states is to use a nonlinear element like a transmon. We present preliminary experimental results obtained with cavity displacements and selective number dependent arbitrary phase gates for universal qudit control, and its application towards High-energy physics (HEP) simulations and beyond. We discuss the advantages and challenges associated with building a 3D SRF architecture while maintaining long cavity lifetimes in the presence of lossy components. We show how the system coherence properties can be preserved by carefully engineering to minimize the participation of the long coherence modes in different loss channels, while ensuring sufficient quantum controllability. We further discuss the path towards building multi-qudit systems.

SQMS

Quantum communications work at SQMS

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The Superconducting Quantum Materials and Systems (SQMS) Center is focused on advancing low-loss interconnectivity between quantum processing units (QPUs) to enable scalable quantum computing. In the short term, our goals include the development and optimization of 2D and 3D platforms with remotely entangled modules, refinement in microwave design and control schemes, and the achievement of high-fidelity quantum state transfer between superconducting

quantum modules. Looking ahead, we aim to realize modular quantum computing with low-loss interconnects, maximize remote entanglement fidelity and implement robust quantum operations with error correction. We will leverage advanced microwave engineering and material science to optimize the performance of quantum interconnects and the coupling interfaces between the interconnects and the QPUs.

SQMS

Quantum sensing for fundamental physics efforts at SQMS

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One of the areas of research of the Superconducting Quantum Systems and Materials (SQMS) center is the application of quantum sensing to fundamental physics searches, demonstrating that quantum sensors can greatly improve the sensitivity of experiments searching for Beyond the Standard Model (BSM) physics, or performing high-precision measurements. Theorists have developed many ideas for BSM physics that would result in interactions that can in principle be detected, but with signals small enough that they haven't been observed yet.

In this field, the capability to lower the detector's thermal noise to few or dozens of mK, and to use QIS technologies such as Josephson Parametric Amplifiers and photon counters (*in-situ* or itinerant) enable us to reach unprecedented sensitivities and faster scan rates.

Here is presented an overview of the quantum sensing efforts at SQMS [1], focusing on theoretical advancements and experimental searches for Dark Sector particles (as dark matter candidates and not), gravitational waves, and precision measurements. The experiments conducted, or under preparation, include axion dark matter (DM) [2, 3], dark photon DM searches [4,5], light-shining-through-wall experiments [6], cavity-based searches for high frequency gravitational waves [7], and measurements of the electron magnetic moment [8].

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SQMS

Quantum Simulations and Algorithms for Condensed Matter and High Energy Physics Applications

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The Condensed Matter/High Energy Physics (CM/HEP) Applications Taskforce within the SQMS Algorithms team has broad interests in quantum simulation spanning quantum dynamics, state preparation, and algorithmic primitives for quantum hardware. We overview three recent papers that touch on each of these directions. First, a collaborative paper involving CM and HEP team members focuses on methods to prepare quantum many-body scar states on quantum computers [1]. Quantum many-body scar states are special eigenstates of complex many-body Hamiltonians that give rise to long-lived coherent dynamics. This dynamics requires nontrivial state preparation, for which various unitary and nonunitary protocols are defined and implemented on IBM and Rigetti hardware. Second, a recent preprint showcases proof of principle results that yield a reduction by more than 3 orders of magnitude of the T-gate costs for simulations of HEP by utilizing more efficient circuit decompositions of non-Abelian Fourier transformations [2]. Third, another recent preprint performs a systematic benchmark of variational quantum eigensolver (VQE) simulations of the Fermi-Hubbard model, an archetypal model of strongly correlated quantum materials [3]. The benchmarks use tensor network methods to investigate idealized VQE simulation accuracy as a function of system size, interaction strength, disorder, and dimensionality, as well as the impact of different choices of variational ansatz. These works lay the foundation for further progress towards quantum utility with near- and intermediate-term quantum hardware.

References:
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[2] E. M. Murairi et al., “Highly-efficient quantum Fourier transformations for some nonabelian groups,” arXiv:2408.00075
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SQMS

SQMS Nanofabrication Taskforce: Towards Fabrication of High Coherence Superconducting Qubits

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https://sqmscenter.fnal.gov/

SQMS Nanofabrication Taskforce, which brings together experts in nanofabrication and materials science at the SQMS Center, has been launched to implement novel materials, substrates, and fabrication techniques for high coherence superconducting quantum devices. In a first coordinated effort, the Nanofabrication Taskforce developed fabrication processes to eliminate the lossy materials at surfaces and interfaces of superconducting qubits to enhance qubit coherence. The initial results of this study demonstrated T1 enhancement by almost an order of magnitude with best T1’s reaching ~ 600 μs. [1] We attribute this improvement to the replacement of lossy native Nb oxide layer with native Ta oxide, which is thinner and less disordered. we are now currently working on strategies with an aim towards moving qubit coherence times to *millisecond* timescales and beyond. The results of a systematic study will be presented to address substrate preparation, alternative materials as low loss platforms (Nb, Ta, and Re), novel non-oxide forming low loss capping layers such as proximitized Au, optimized qubit designs, and optimized Josephson junction materials, processing, and design.

[1] *npj Quantum Inf* **10**, 43 (2024)

SQMS

SQMS Quantum R&D in Machine Learning, Optimization and Sensing beyond Fundamental Physics Applications

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This newly formed team at SQMS under the Ecosystem Thrust seeks to develop capabilities impacting societal advances beyond the core domain of HEP and condensed matter physics. We explicitly leverage the experimental and algorithmic innovations developed across all groups and connect to the broad-scope external projects of the diverse team of PIs. As the inaugural set of projects, we are studying numerically quantum machine learning models inspired by efficiently trainable echo-state and orthogonal neural networks and developing designs for related experiments to be performed on quantum processors based on SQMS SRF cQED technology and Rigetti's transmon arrays. Investigated models exploit ideas and lessons learned from multiple prior work by SQMS team members in a variety of internal and external activities [1, 2]. Target initial applications include noisy signal processing, potentially captured by quantum sensors or noisy QPUs, as well as simulation and classification of healthcare data. For instance, image reconstruction of the brain's electrical properties by solving the inverse Maxwell equation problem with uncertainty [R2] through a hybrid quantum-classical physicsinformed architecture for time-dependent processes [3]. The group is also investigating the application and development of novel quantum sensors based on the magnetic levitation of a superconducting sphere coupled to a superconducting qubit. This coupling enables high-precision measurements of the position of the sphere, which can be used for sensitive detection of forces, enabling practical applications such as gravimetry for geophysics analysis or accelerometry for GPS-denied navigation [4].

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SQMS

SQMS Science Advances Impact on Rigetti Commercial Processors

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The collaboration between the Superconducting Quantum Materials and Systems Center (SQMS) and Rigetti Computing produced several advancements in our understanding of the role of materials characteristics in quantum processor performance. This partnership leverages SQMS's extensive characterization infrastructure and cutting-edge research in materials, and Rigetti's expertise in quantum hardware and robust nanofabrication to improve precision and performance of Rigetti's test QPUs. Qubit frequency is determined in large part by the properties of Josephson junctions (JJs) made of amorphous oxide tunnel barriers; the Alternating-Bias Assisted Annealing (ABAA) process allows us to tune JJs to their desired frequency [1]. Work by SQMS researchers in characterizing high-precision JJs post-processed (using ABAA) have yielded crucial information on the nature of the structure and chemical bonding uniformity of the ABAA processed amorphous oxides. Performance has also been improved through a comprehensive series of experiments that tested encapsulation and surface treatment. Encapsulation of the niobium metal layer with tantalum resulted in a T_1 improvement of 80%, experimentally confirming the role of Nb surface losses in qubit performance [2]. Pre-treatment of the underlying silicon surface prior to JJ fabrication by replacing a buffered oxide etch (BOE) with hydrofluoric acid (HF) followed by aqueous ammonium fluoride (NH4F) has shown a statistically significant improvement of T_1 by 22%, and reduction in the number of strongly coupled TLS [3]. These examples, as well as many other published and ongoing investigations, demonstrate the mutual benefits that come from Rigetti's involvement in the SQMS collaboration.

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SQMS

Superconducting characterization efforts of qubit materials across SQMS center

Maria Iavarone [1], Junki Makita[1], Seth Rice [1,2], Kevin Ryan[3], Max Wisne[3], Yanpei Deng[3], Venkat Chandrasekar [3], Kamal R. Joshi [4], Amlan Datta[5], Bicky Moirangthem[5], Ruslan Prozorov [4,5], Mehdi Zarea[6], Aziz Abogoda[6], Jim Sauls [6], and John Zasadzinski [2]

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The superconducting characterization efforts within SQMS focus on probing superconductivity across various length scales. These include atomic-scale investigations using scanning tunneling microscopy and spectroscopy (STM/STS), meso-scale studies with magneto-optical imaging, and bulk measurements through London penetration depth and magnetization. This comprehensive approach allows us to detect superconductivity suppression and pinpoint pair-breaking centers. This critical information is quickly communicated to fabrication teams, enabling near real-time feedback to enhance device performance.

High-resolution phase boundary measurements provide rapid quality assessments of Nb films, revealing crystal grain structure and disorder. STM/STS studies of Nb thin films and single crystals have uncovered nanoscale defects near surfaces and at grain boundaries, linked to Nb oxides, which exhibit sub-gap states. On the other hand, Nb films capped with Au or Re show BCS-like quasiparticle DOS with zero sub-gap conductance over broad areas, indicating effective reduction of quasiparticle diffusion via the proximity effect. Transport measurements of Josephson junctions reveal that intrinsic noise sources in transmons reduce critical current and cause zero bias resistance, potentially impacting decoherence in superconducting qubits.

Theoretical developments include computational tools using DFT and Eliashberg theory for superconducting films and devices. These models address impurity-induced disorder (O, N, H/D interstitials), NbH inclusions, and TLS centers, predicting disorder effects on Nb films and resonators. The development of analysis tools for STM/PCT spectroscopy of sub-gap excitations and inverting London penetration measurements to obtain sub-gap spectra is in progress. Overall, these results provide valuable insights for designing next-generation devices with enhanced performance and reliability.

SQMS

Tools for Quantum Algorithms, Protocols, Benchmarking, Architectural Design and Codesign

Eleanor Rieffel[1], Sohaib Alam[1,2], Nishchay Suri[1,2], Jason Saied[1], Davide Venturelli[1,2], Nicholas Bornman[3], Tanay Roy[3], Joshua A Job[4], Namit Anand[15], Gabriel N Perdue[3], Silvia Zorzetti[3], Ahmed A. Akhtar[6], Jeffrey Marshall[1,2], Yi-Zhuang You[6], Andrew Hardy[7], Priyanka Mukhopadhyay[7], Robert Konik[8], Layla Hormozi[8], Stuart Hadfield[12], João Barata[8], Raju Venugopalan[8], Dmitri E. Kharzeev[8], Nathan Wiebe[7,9], Shantom K. Borah[10], Asit K. Pradhan[10], Nithin Raveendran[10], Narayanan Rengaswamy[10], and Bane Vasić[10]

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We highlight the work of several teams at SQMS involved in quantum algorithms, benchmarking, and architectural design as well as error correction and mitigation. Work in these directions informs future strategies for co-designing the physical hardware, the error correction protocols we would employ, and the algorithms we would run on the fault-tolerant device, including key experimental and algorithmic milestones along the path towards practical quantum advantage in quantum simulation for high-energy physics and beyond.

As examples of such work, we describe robust protocols [1] to benchmark the controllability of individual qudits in SQMS 3D hardware using sampling tests and by simulating the dominant noise sources we expect in the hardware. We explain advantages of error mitigation protocols [2] that can exploit the natural dissipative dynamics of the hardware. We give an overview of progress made towards efficient tomography protocols [3] suitable for qudit architectures. We review a collaborative paper [4] between SQMS and C2QA on simulating a simple quantum field theory that includes a detailed resource analysis of the physical gate and qubit counts to run the algorithms on fault-tolerant qubit-based hardware assuming the surface code as the error correction protocol. Finally, we discuss the development of qudit-based low-density parity check (LDPC) codes [5] that have asymptotically good encoding rates and distance, and that can be employed for error correction on SQMS qudits.

[1] "Benchmarking the algorithmic reach of a high-Q cavity qudit", N. Bornman et al., arXiv:2408.13317
[2] "Uniformly Decaying Subspaces for Error Mitigated Quantum Computation", N. Suri, J. Saied, D. Venturelli, arXiv:2403.00163
[3] "Dual-Unitary Classical Shadow Tomography", A. A. Akhtar, N. Anand, J. Marshall, Y. You, arXiv:2404.01068
[4] "Optimized Quantum Simulation Algorithms for Scalar Quantum Field Theories", A. Hardy et al., arXiv:2407.13819
[5] "Non-Binary Hypergraph Product Codes for Qudit Error Correction, " S. K. Borah, A. K. Pradhan, N. Raveendran, N. Rengaswamy, B. Vasić, the 2024 IEEE International Conference on Quantum Computing and Engineering (QCE) [accepted]

SQMS

Understanding and Improving 2D QPU Gate Fidelities at SQMS Center

Mustafa Bal[1], Andrew Bestwick[2], Nicholas Bornman[1], Francesco Crisa[1], Vinh San Dinh[3], Sabrina Garattoni[1], Anna Grassellino[1], Alysson Gold[2], Ziwen Huang[1], Paul Heidler[1], Glenn Jones[2], Taeyoon Kim[3], Yao Lu[1], Andrei Lunin[1], Akanksha Mishra[1], Akshay Murthy[1], Ivan Nekrashevich[1], Alexander Romanenko[1], Tanay Roy[1], Prasad Sarangapani[2], Ben Scharmann[2], Mehrnoosh Vahidpour[2], David van Zanten[1], Xinyuan You[1], Shaojiang Zhu[1], and Silvia Zorzetti[1]

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The understanding and improvement of the quantum gate fidelities are crucial for resource-efficient quantum error correction and many practical quantum applications. At SQMS Center, we are devoted to optimizing the current gate implementations on 2D superconducting platforms from the perspectives of both material/layout innovation and gate scheme optimization. In this poster, we show our progress on the experimentation with the coherence measurement of coupled qubits vs. isolated qubits, as well as the comparison between them. We also showcase our progress on tuning up and implementing entangling gates on a commercial quantum processor from Rigetti Computing stationed at Fermilab. Lastly, we lay out our proposal of a novel gate scheme toward faster gate operations and higher fidelities.

SQMS

Understanding and Mitigating Materials-Level Sources of Loss in Superconducting Qubits

Akshay A. Murthy[1], Mustafa Bal[1], Shaojiang Zhu[1], Francesco Crisa[1], Jaeyel Lee[1], Zuhawn Sung[1], Maithilee Shinde[1,6], Andrei Lunin[1], Daniel Bafia[1], Yulia Krasnikova[1], Cameron J. Kopas[2], Ella O. Lachman[2], Josh Y. Mutus[2], Hilal Cansizoglu[2], Jayss Marshall[2], David P. Pappas[2], Jin-Su Oh[3], Lin Zhou[3], Kamal Joshi[3], Amlan Datta[3], Sunil Ghimire[3], Makariy Tanatar[3], Ruslan Prozorov[3], Richard Kim[3], Sam Haeuser[3], Joong-mok Park[3], Jigang Wang[3], Matthew J. Kramer[3], Dominic P. Goronzy[4], Mitchell Walker[4], Celeo Diaz[4], Mark Hersam[4], David Garcia[4], William Mah[4], Michael Bedzyk[4], Peter G. Lim[4], Vinayak P. Dravid[4], Dieter Isheim[4], David Seidman[4], Kevin Ryan[4], Yanpei Deng[4], Maxwell Wisne[4], Venkat Chandrasekhar[4], Junki Makita[5], Maria Iavarone[5], Seth Rice[6], John Zasadzinski[6], Tony McFadden[7], Florent Lecocq[7], Corey Rae McRae[7], David Olaya[7], Peter Hopkins[7], James A. Sauls[8], Alexander Romanenko[1], and Anna Grassellino[1]
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Advances in our understanding of materials has played a crucial role driving recent increases in achievable coherence times and gate fidelities in superconducting transmon qubits.
This includes identifying defects, impurities, interfaces, and surfaces present within the device geometry as well as implementing new strategies to mitigate the deleterious effects introduced by these disordered regions. As part of the SQMS center, we have deployed a wide variety of unique materials characterization techniques in tandem with superconducting as well as microwave measurements to examine sources of loss in these devices. Some of these materials characterization techniques include scanning/transmission electron microscopy, x-ray diffraction/reflectivity, scanning probe microscopy, secondary ion mass spectrometry, and atom probe tomography performed at both room temperature and cryogenic temperatures. Through this effort, researchers have identified a wide variety of defective structures that can potentially introduce two-level systems (TLS) or non-TLS dissipation in superconducting qubits [1-10].

Recently, as part of a comprehensive and coordinated study, qubit chips with known performance variations have been distributed and probed across multiple institutions, including Ames Lab, Northwestern, and Fermilab. These qubits have been interrogated with a wide variety of non-destructive and destructive methods. This approach aims to pinpoint the underlying materials-level causes of device discrepancies and this collaborative effort involving over 40 researchers in the materials science domain represents a significant stride in quantum computing research, particularly in the analysis of high coherence qubits. Preliminary findings suggest a correlation between variations in magnetic flux penetration, impurity concentrations, and sidewall geometries with the overall microwave loss across different devices. These insights, derived from a blind study, are poised to enhance the understanding of qubit behavior.

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[4] Jin-Su Oh et al., "Structure and Formation Mechanisms in Tantalum and Niobium Oxides in Superconducting Quantum Circuits", ACS Nano (2024), DOI 10.1021/acsnano.4c05251.
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[6] A. A. Murthy et al., "Developing a Chemical and Structural Understanding of the Surface Oxide in a Niobium Superconducting Qubit," ACS Nano 16, 10, 17257–17262 (2022).
[7] Jin-Su Oh et al., "In-situ transmission electron microscopy investigation on surface oxides thermal stability of niobium," Applied Surface Science, 627, 157297 (2023).
[8] Jaeyel Lee et al., "Discovery of Nb hydride precipitates in superconducting qubits," arXiv:2108.10385 (2021)
[9] A. A. Murthy et al.,, "TOF-SIMS Analysis of Decoherence Sources in Nb Superconducting Resonators," Appl. Phys. Lett. 120, 044002 (2022).
[10]Jaeyel Lee et al., "Stress- induced omega (ω) phase transition in Nb thin films for superconducting qubits," Phys. Rev. Materials 7, L063201 (2023)

SQMS

What Affects Single Qubit Performance?

Corey Rae H. McRae[1,2], Jorge Ramirez[1,2], Andre Vallieres[3], Tanay Roy[4], David van Zanten, Ella Lachman[5], Manuel Castellanos Beltran[2], Pete Hopkins[2], and Josh Mutus[5]

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Superconducting qubit coherence exhibits large temporal fluctuations due to strongly-coupled defects, in addition to being influenced by environmental factors. It is an open question whether reproducible coherence metrics can be measured for a single qubit at different laboratory sites. This question is critical, as qubit coherence is one of few available metrics for engineering better qubits through microwave design, materials, and fabrication updates. In this poster, SQMS' efforts towards a superconducting qubit interlaboratory comparison (the SQMS Round Robin) are outlined.

Posters by Number

Poster Number - Center – Title of Poster Abstract
Posters 1-5 are the NQISRC Overview Posters. Posters 6-85 are in alphabetical order.

1 - C^2QA – C^2QA Overview

2 - Q-NEXT – Q-NEXT: Advancing Science for Breakthroughs in Quantum Communication, Sensing and Computing

3 - QSA – QSA – Quantum Systems Accelerator

4 - QSC – Quantum Science Center

5 - SQMS – Research Efforts Across the SQMS center

6 - C^2QA – A Unitary Encoder of Surface Code

7 - QSA – Advances in Self-Contained Control Hardware

8 - C^2QA – Advancing Quantum Computing with the Aid of Materials Science

9 - Q-NEXT – Argonne Quantum Foundry

10 - SQMS – Cavity-Based Microwave Characterization for Calculating Losses in Superconducting Qubits

11 - QSC – Completion of the Quantum Underground Instrumentation Experimental Testbed (QUIET)

12 - QSC – Designing Materials to Enhance Topological Superconductivity for Quantum Computing Applications

13 - QSA – Detection and cooling of atoms without destroying the encoded quantum information

14 - C^2QA – Development of a Generic Multimodal Scanning Probe Testbed

15 - Q-NEXT – Diamond Membranes for Quantum Technologies

16 - SQMS – Disentangling the Impacts of Quasiparticle and Two-Level System on the Statistics of the Superconducting Qubit Lifetime

17 - C^2QA – Dispersive Non-reciprocity Between a Qubit and a Cavity

18 - Q-NEXT – Engineering Dark Spin-Free Diamond Surfaces

19 - Q-NEXT – Engineering Molecular Qubits for Sensing and Communication

20 - C^2QA – Error Detection and Error Correction with Superconducting Circuits: The Microwave Cavity Dual-Rail

21 - QSC – Estimating the Energy Threshold of Qubit-based Detectors in a Relaxation Sensing Scheme

22 - SQMS – Evaluating Radiation Impact on Superconducting Transmon Qubits in Above and Underground Facilities

23 - QSC – Experimental Evaluation of Quantum Spin Liquids Using Protocols

24 - C^{2}QA – Exploring Quantum Materials with Ultrabroadband Infrared-THz Nanoscopy

25 - QSC – First Measurement of Correlated Charge Noise in Superconducting Qubits at an Underground Facility

26 - C^{2}QA – Hidden Hydrogen at Interfaces of Niobium and Tantalum Oxides for Quantum Applications

27 - C^{2}QA – High-Fidelity Preparation of Ground-States and Gates Using Adaptive Ansätze and Tunable Pulses

28 - C^{2}QA – Hybrid Oscillator-qubit Quantum Processors: Instruction Set Architectures, Abstract Machine Models, and Applications

29 - Q-NEXT – Initial Stages of Development of Er-doped CeO2 on Silicon as a Quantum Memory Platform

30 - QSC – In-situ ARPES Study on magnetic-topological-superconducting Heterostructures and Direct Observation of an Interfacial Topological Superconducting States

31 - Q-NEXT – Integrating spin qubits within silicon carbide technologies

32 - QSC – Leveraging Genetic Strategies and Hybrid Classical-Quantum Computing for Quantum Circuit Design

33 - QSA – Macrostates vs. Microstates in the Classical Simulation of Critical Phenomena in Quench Dynamics of 1D Ising Models

34 - SQMS – Material and Interface Engineering Strategies to Mitigate Decoherence in Superconducting Qubits

35 - Q-NEXT – Nanocavity-mediated Purcell enhancement of Er in TiO2 thin films grown via atomic layer deposition

36 - QSA – Noise induced regression to classical dynamics in the single mode Kerr effect

37 - QSC – NWQSim: An Integrated Quantum System Simulation Package

38 - QSA – Observation of a Finite-Energy Phase Transition in a One-Dimensional Quantum Simulator

39 - C^{2}QA – Observation of Discrete Charge States of a Coherent Two-Level System in a Superconducting Qubit

40 - Q-NEXT – Optical Control and Readout of Isotopically Engineered Molecular Color Centers

41 - QSA – Optical Tweezer Arrays of Ultracold Molecules

42 - QSC – Oqtant; a neutral atom quantum matter testbed and service for all

43 - C^{2}QA – Parametric Controls for Quantum Modules, Single Qubit Gates, and Longitudinal Qubit Readout

44 - QSC – Photonic Quantum Computing and Sensing at the QSC

45 - SQMS – Progress on 3D SRF-based architecture for quantum computing

46 - QSC – QICK-in-a-box. The Quantum Instrumentation Control Kit for QIS

47 - QSA – Quantum Coarsening and Collective Dynamics on a Programmable Quantum Simulator

48 - SQMS – Quantum communications work at SQMS

49 - QSC – Quantum Enhanced Impulse Measurements with Mechanical Sensors in the Search for Dark Matter

50 - C^{2}QA – Quantum Memory: A Missing Piece in Quantum Computing Units

51 - QSA – Quantum metrology and simulation with matter-waves in a high-finesse cavity

52 - QSA – Quantum Metrology with Alkaline-Earth Atom Arrays

53 - QSC – Quantum phases of Rydberg atoms on Shastry - Sutherland lattice

54 - SQMS – Quantum sensing for fundamental physics efforts at SQMS

55 - C^{2}QA – Quantum Simulation in the Path Integral Representation

56 - QSA – Quantum Simulation of Spin-Boson Models with Structured Bath

57 - SQMS – Quantum Simulations and Algorithms for Condensed Matter and High Energy Physics Applications

58 - QSA – Quantum Simulations of High Energy Physics At Large N

59 - QSC – Quantum Simulations of the Schwinger Model: State Preparation and Time Evolution using 100+ Qubits

60 - C^{2}QA – QuIRC: Co-design of Superconducting Quantum Interface Routing Card for Lattice Surgery of Surface Codes

61 - Q-NEXT – Room-Temperature Valley-Selective Emission Enabled by Chiral Quasi-Bound States in the Continuum

62 - QSA – Simulating Meson Scattering on Spin Quantum Simulators

63 - QSC – Simulating Superconducting Devices in Novel Materials Using the G4CMP Simulation Toolkit

64 - QSA – Site-selective cavity readout and classical error correction of a 10-bit atomic register

65 - Q-NEXT – SLAC Superconducting Quantum Foundry

66 - SQMS – SQMS Nanofabrication Taskforce: Towards Fabrication of High Coherence Superconducting Qubits

67 - SQMS – SQMS Quantum R&D in Machine Learning, Optimization and Sensing beyond Fundamental Physics Applications

68 - SQMS – SQMS Science Advances Impact on Rigetti Commercial Processors

69 - Q-NEXT – Stroboscopic X-ray diffraction microscopy of dynamic strain in diamond thin-film bulk acoustic resonators for quantum control of nitrogen-vacancy centers

70 - SQMS – Superconducting characterization efforts of qubit materials across SQMS center

71 - QSA – Tailoring Molecular Clusters with Quantum Computers

72 - C^2QA – Temperature and Magnetic-Field Dependence of Relaxation in a Fluxonium Qubit

73 - Q-NEXT – The Chicago Quantum Computing Testbed at Argonne National Laboratory

74 - QSA – The Zeno Effect: A Versatile Tool for Quantum Control & Computation

75 - SQMS – Tools for Quantum Algorithms, Protocols, Benchmarking, Architectural Design and Codesign

76 - QSC – Topological insulator/superconductor hybrid devices: from Josephson junctions to antidots

77 - Q-NEXT – Towards a network of quantum registers with neutral atoms using parabolic mirrors and pre-aligned optics

78 - QSA – Towards Dipolar Quantum Magnetism with Ytterbium Rydberg Atom Arrays

79 - Q-NEXT – Towards Quantum Networking: Tin Vacancy in Diamond

80 - Q-NEXT – Trilayer Superconducting Qubits Operating at High Temperatures

81 - QSC – TRSB and Axions in Topological Quantum Matter

82 - SQMS – Understanding and Improving 2D QPU Gate Fidelities at SQMS Center

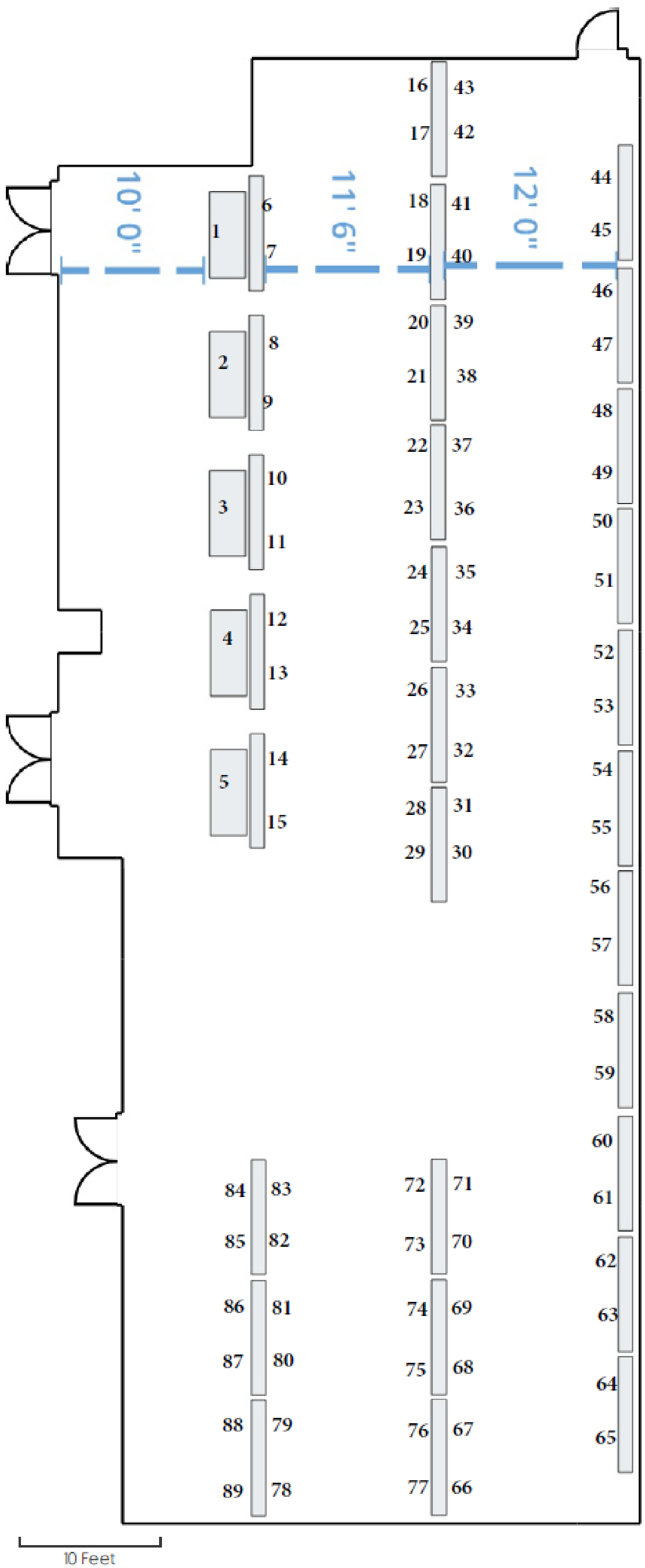
83 - SQMS – Understanding and Mitigating Materials-Level Sources of Loss in Superconducting Qubits

84 - C^2QA – Vortex Motion Induced Losses in Tantalum Resonators

85 - SQMS – What Affects Single Qubit Performance?

Poster Layout

Posters will be located in the Roosevelt/Madison Room.



Select Abstracts: Day 2 Technical Highlights

In Presentation Order

QSA

Tuning a Many-Body System of Polar Molecules

Annette N. Carroll[1*], Henrik Hirzler[1], Calder Miller[1], David Wellnitz[1], Sean R. Muleady[1,2], Junyu Lin[1], Krzysztof P. Zamarski[1,3], Reuben R. W. Wang[1], Haoyang Gao[4], Hengyun Zhou[4,5], Mikhail D. Lukin[4], John L. Bohn[1], Ana Maria Rey[1], and Jun Ye[1*]

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Ultracold molecules enable exploration of many-body physics due to their highly tunable dipolar interactions. In this presentation, I will review our recent observations of out-of-equilibrium spin dynamics with polar molecules. With spin encoded in the lowest rotational states of the molecules, we realized a generalized *t-J* model with dipolar interactions [1]. We explored the role of dipolar couplings tuned with dc electric fields and the effect of motion regulated by optical lattices on Ramsey contrast decay, pushing the limits of current theoretical understanding. Further, we used Floquet engineering to realize a two-axis twisting Hamiltonian, inaccessible with static fields, and studied its mean-field dynamics [2]. This work sets the stage for future explorations of exotic spin Hamiltonians with the tunability of molecular platforms.

[1] A. N. Carroll et al., Observation of Generalized t-J Dynamics with Tunable Dipolar Interactions, arXiv:2404.18916.
[2] C. Miller et al., Two-axis twisting using Floquet-engineered XYZ spin models with polar molecules, arXiv:2404.18913.

SQMS

Optimizing Superconducting Qubits: Insights into Oxides Microstructures

Jin-Su Oh,[1] Cameron J. Kopas,[2] Hilal Cansizoglu,[2] Joshua Y. Mutus,[2] Kameshwar Yadavalli,[2] Akshay A. Murthy,[3] Mustafa Bal,[3] Francesco Crisa,[3] Shaojiang Zhu,[3] Carlos G. Torres-Castendo,[4] Rahim Zaman,[5] Dapeng Jing,[6] John Zasadzinski,[7] Anna Grassellino,[3] Alex Romanenko,[3] Mark C. Hersam,[4] Michael J. Bedzyk,[4] Matt Kramer,[1] Bi-Cheng Zhou,[5] and Lin Zhou[1,6]

[1] Ames National Laboratory; [2] Rigetti Computing; [3] Fermi National Accelerator Laboratory; [4] Northwestern University; [5] University of Virginia; [6] Iowa State University; [7] Illinois Institute of Technology

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Improving qubit lifetime is essential for fault-tolerant quantum computing. It is widely acknowledged that intricate processing techniques introduce defects at the interfaces and

surfaces of superconducting quantum circuits, which can create sources of decoherence. Therefore, a precise understanding of how a material's structure contributes to decoherence is critical for enhancing the performance of superconducting qubits. This talk highlights our recent advancements in understanding surface oxides in resonators and ultrathin aluminum oxide barriers in Josephson junctions (JJs).

The SQMS center demonstrated that encapsulating niobium surfaces with a ~10nm tantalum layer results in 2-5x longer T1 compared to bare niobium. Our collaborative investigation shows that this improvement is attributed to tantalum's less lossy surface oxide, which contains fewer sub-oxides than niobium oxide. Moreover, the amorphous Ta_2O_5 shows a bonding nature closer to crystalline form than amorphous Nb_2O_5, potentially reducing hydrogen diffusion toward the oxide/metal interface.[1,2]

We also explored the effect of aluminum deposition rates on aluminum oxide microstructure and qubit lifetime. Although increasing the deposition rate from 0.5 Å/s to 5 Å/s significantly improved oxide layer roughness and thickness variation, the qubits' coherence time remained unchanged. This is likely due to Cooper pairs only tunneling through the thinnest parts of the barrier, making them less affected by the grain boundaries in the aluminum thin films. Additionally, we uncovered a stress-induced grain boundary sliding mechanism, which contributes to short-circuit failures in JJs. Our discovery provides vital insight into oxide microstructure and superconducting qubits' functionality.[3]

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C²QA

Promising Materials for Making Qubits

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Work at C²QA has established that replacing the traditionally used superconducting niobium or aluminum films with tantalum leads to significant improvements in qubits coherence times. To guide further improvements in coherence times, we have investigated suspected sources of energy loses on these films related to the different kinds of tantalum oxides that form on tantalum's surface when it is exposed to air. Based on this knowledge, we have improved the film properties by coating tantalum with a thin layer of magnesium that prevented the material's oxidation. We have also explored potential paths for integrating quantum computation with silicon technology, examining the electrical transport properties of superconducting quantum devices based on PtSi. We have further developed a systematic approach to understanding how energy is lost from the materials that make up qubits, working with collaborators from the Devices Thrust of C^2QA.

QSA

Quantum Simulation on a Two-Dimensional Superconducting Qubit Array

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https://quantumsystemsaccelerator.org/

Arrays of coupled superconducting qubits are a compelling platform for analog quantum simulations of solid-state matter as they natively emulate the Bose-Hubbard model while offering a high degree of control, fast operation rates, and site-resolved readout. Here, we discuss three recent experiments using a two-dimensional array of superconducting qubits designed for digital/analog hybrid operation [1]. First, we drive all qubits simultaneously to prepare highly entangled many-body states with tunable energy. By increasing the energy of the states, we observe a transition from area-law to volume-law entanglement scaling [2]. Second, we adopt a parametric coupling scheme that emulates an adjustable synthetic magnetic vector potential. We verify that spatial gradients of the vector potential create a synthetic magnetic field, and time variation creates a synthetic electric field [3]. Finally, we emulate a lattice with adjustable bandwidth and study localization dynamics in the transition from a conventional band structure to flat bands.

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SQMS

Where is Quantum Utility in Particle Physics?

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https://sqmscenter.fnal.gov/

Particle physics requires quantum computers. This broad statement has developed acuity in the past four years through both identification of specific applications and in resource estimates for achieving them. In this talk, I will discuss the co-design efforts between theory, algorithms, and hardware researchers within SQMS that have reduced particle physics benchmarks from quantum exascale-years to the same regime as other benchmarks such as breaking RSA-2048 and the state of FeMoCo.

C²QA

Spin-photon entanglement of a single Er^{3+} ion in the telecom band

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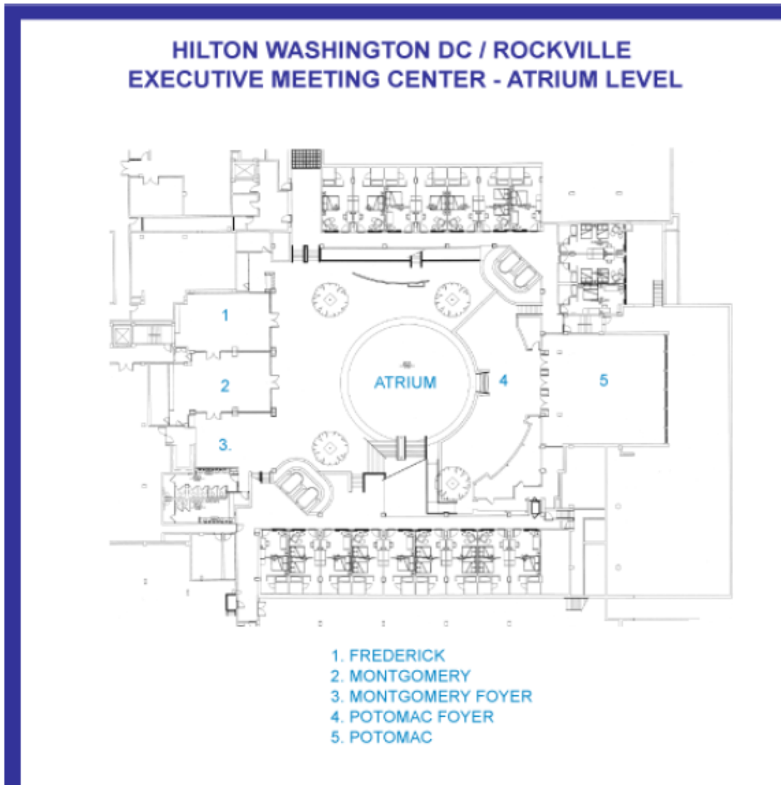
[1]Princeton University

Entanglement between photons and a quantum memory is a key component of quantum repeaters, which allow long-distance quantum entanglement distribution in the presence of fiber losses. Spin-photon entanglement has been implemented with a number of different atomic and solid-state qubits with long spin coherence times, but none directly emit photons into the 1.5 μm telecom band where losses in optical fibers are minimized. Here, we demonstrate spin-photon entanglement using a single rare earth ion in the solid state, Er^{3+}, coupled to a silicon nanophotonic cavity, which directly emits photons at 1532.6 nm. We observe an entanglement fidelity of 73(3)% after propagating through 15.6 km of optical fiber. This work opens the door to large-scale quantum networks based Er^{3+} ions, leveraging scalable silicon device fabrication and spectral multiplexing.

Hotel Map



- Over 35,000 sq. ft. of flexible meeting space
- Convenient onsite garage parking
- Max capacity in theater is 600
- Max capacity in classroom is 300
- Central atrium offering over 8,000 sq. ft. of open space for receptions, exhibits & meals
- Inclusive packages & exceptional culinary staff
- STEPS away from Twinbrook Metro (DC Red Line)
- City environment within walking distance to shops, restaurants and a 24-hr grocery store

- 315 Guest Rooms, including suites, Queen Queens, Kings and accessible rooms
- Mini refrigerator, coffee machines, and safety deposit boxes are standard in all rooms
- Pike Café, serving Starbucks in our spacious lobby
- Olive's Modern American Bistro is open for breakfast, lunch, happy hour & dinner
- 24 hour Pavilion Pantry Market
- 24 hour state-of-the art Fitness Center