Program Summary
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Workshop Day 1: Tuesday 9 July
@ Institute for Quantum Computing
08.45 - 09.00: Welcome
09.00 - 09.40: Maciej Lewenstein' group: Pavel Popov
Title: Quantum simulation of lattice gauge theories with qudit systems

09.40 - 10.20: Ray Laflamme's group: Cristina Rodriquez, Matt Graydon
Title: Platonic Ququart Benchmarking

10:20 - 10:50: Coffee Break (30min)

10.50 - 11.30: Michel Devoret's group: Benjamin Brock
Title: Quantum Error Correction of Bosonic Qudits Beyond Break-even

11.30 - 12:10: Irfan Siddiqi's group: Noah Goss, Larry Chen
Title: Entangling Superconducting Qudits

12.10 - 12.50: Barry Sanders
Title: Kittens, Cats, Combs & Compasses: Superposing Coherent States

12.50 - 14.00: Lunch Break (70min)

14.00 - 14.40: Hubert de Guise
Title: Simple factorization and other ``nice'' properties of d-dimensional unitaries

14.40 - 15.20: Sahel Ashhab
Title: Optimizing control of quantum information in higher dimensions: (1) qutrit control and (2) speed limits for two-qubit gates with weakly anharmonic qubits

15.20 - 16.00: Martin Ringbauer
Title: Quantum Computing and Simulation with Trapped-Ion Qudits

16.00 - 16.30: Coffee Break (30min)

16.30 - 17.10: Adrian Lupascu
Title: Control and process characterization in superconducting qutrits

17.10 - 17.50: Susanne Yelin
Title: Quantum chemistry with a quantum computer

18.00 - 20.00 = Poster Session + Handheld Food

Workshop Day 2: Wednesday 10 July
@ Institute for Quantum Computing

09.10 - 09.20: Welcome

09.20 - 10.00: Eleanor Crane
Title: Hybrid Oscillator-Qubit Quantum Processors: Simulating Fermions, Bosons, and Gauge Fields

10.00 - 10.40: Sabre Kais
Title: Simulation of Chemical Reactions on a Quantum Computer

10:40 – 11.10: Coffee Break (30min)

11.10 – 11.50: Crystal Senko
Title: High-dimensional qudit control in trapped ions for quantum computing and quantum simulation

11.50 - 12.30: Ashok Ajoy
Title: New advances towards deployable quantum sensors

12.30 - 13.40: Lunch Break (70min)

13.40 - 14.10: Jacqui Romero
Title: Towards qudit quantum computation

14.10 - 14.50: Joe Emerson
Title: Hardware and Software Development Tools for Qudit Experiments

14.50 - 15.20: Coffee Break (30min)

15.20 - 16.00: Lia Yeh
Title: TBA

16.00 - 17.10: Panel discussion

17.10 - 17.30: Group Foto

17.30 - 18.15: Walk to Conference dinner

18.15 - 21.00: Conference Dinner for invited speakers

Abstracts

Workshop Day 1: Tuesday 9 July
@ Institute for Quantum Computing

09.00 - 09.40: Maciej Lewenstein' group: Pavel Popov
Title: Quantum simulation of lattice gauge theories with qudit systems
Abstract: TBA

09.40 - 10.20: Ray Laflamme's group: Cristina Rodriquez, Matt Graydon
Title: Platonic Ququart Benchmarking
Abstract: TBA

10.50 - 11.30: Michel Devoret's group: Benjamin Brock
Title: Quantum Error Correction of Bosonic Qudits Beyond Break-even
Abstract: Hilbert space dimension is a key resource for quantum information processing. A large Hilbert space is not only an essential requirement for quantum error correction, but it can also be advantageous for realizing gates and algorithms more efficiently. There has thus been considerable experimental effort in recent years to develop quantum computing platforms using qudits (d-dimensional quantum systems with d>2) as the fundamental unit of quantum information. Just as with qubits, quantum error correction of these qudits will be necessary for delivering on their promise in the long run, but to date error correction of logical qudits has not been realized experimentally. Here we present the first experimental demonstrations of error-corrected logical qutrits (d=3) and ququarts (d=4) by employing the Gottesman-Kitaev-Preskill (GKP) bosonic code [1] in a circuit QED architecture. Using a reinforcement learning agent [2] we optimize the GKP qutrit (ququart) as a ternary (quaternary) quantum memory and demonstrate beyond break-even error correction with a gain of 1.82 ± 0.03 (1.87 ± 0.03). In addition to these demonstrations, this work opens up many new research directions for quantum information processing with bosonic qudits. [1] Gottesman, Kitaev, Preskill, PRA (2001) [2] Sivak et al., Nature (2023)

11.30 - 12:10: Irfan Siddiqi's group: Noah Goss, Larry Chen
Title: Entangling Superconducting Qudits
Abstract: Quantum processors with of order a few hundred qubits based on superconducting circuitry have demonstrated computing power on par with the most advanced classical supercomputers for certain problems. Currently, most quantum processors operate two-level quantum systems, or qubits. The computational power of these near-term devices can be further boosted by leveraging multi-level approaches to encode quantum information in the larger and more connected Hilbert space of d-level systems (or qudits). In my talk, I will describe our work to realize qudit-based quantum computing platforms built from superconducting circuits and specifically focus on our recent works enabling efficient entanglement of qudits in the superconducting platform.

Abstracts

12.10 - 12.50: Barry Sanders

Title: Kittens, Cats, Combs & Compasses: Superposing Coherent States

Abstract: Superpositions of coherent states, which have minimum uncertainty and follow, at least transiently, classical motion, constitute codes for quantum computing, enhance quantum communication and are advantageous for quantum sensing and metrology. I present a potted history of this field followed by making a nuclear cat state on a nuclear qudit.

14.00 - 14.40: Hubert de Guise

Title: Simple factorization and other ``nice'' properties of d-dimensional unitaries

Abstract: I will describe a ``nice'' construction of d-dimensional unitaries that lead to convenient factorization properties for the transformation, and for the resulting Haar measure. Some average properties of the unitaries will also be discussed.

14.40 - 15.20: Sahel Ashhab

Title: Optimizing control of quantum information in higher dimensions: (1) qutrit control and (2) speed limits for two-qubit gates with weakly anharmonic qubits

Abstract: We consider two aspects of quantum information processing when the physical system used to encode the quantum information possesses more than two quantum states in the accessible energy range, as is the case for superconducting devices. On one hand, these devices can be used to encode qudits. In this context, we investigate the optimal implementation of single-qudit gates with superconducting qudits. In particular, we show that it is possible to perform an arbitrary gate using a single pulse with resonant drive frequencies. We also consider the implementation of qubit gates when the presence of higher energy levels cannot be ignored. We use optimal control theory to determine the maximum achievable gate speed for two-qubit gates in the qubit subspace of the many-level Hilbert space. We identify two competing mechanisms. On one hand, higher energy levels are generally more strongly coupled to each other. Under suitable conditions, this stronger coupling can be utilized to make two-qubit gates significantly faster than the reference value based on simple qubits. On the other hand, a weak anharmonicity typically constrains the speed at which a quantum system can be adequately controlled. In order to account for this constraint, we modify the pulse optimization algorithm to avoid pulses that lead to appreciable population of the higher levels. In this case, we find that the presence of the higher levels can lead to a significant reduction in the gate speed. These results can help the search for optimized gate implementations and provide guidelines for desirable conditions on anharmonicity to enable the utilization of the higher levels in realistic systems. This work was supported by MEXT Quantum Leap Flagship Program Grant No. JPMXS0120319794.

15.20 - 16.00: Martin Ringbauer

Title: Quantum Computing and Simulation with Trapped-Ion Qudits

Abstract: TBA

Abstracts

16.30 - 17.10: Adrian Lupascu

Title: Control and process characterization in superconducting qutrits

Abstract: Superconducting circuits provide a versatile platform for the implementation of qudits. In the first part of my presentation, I will discuss the implementation of quantum control and process characterization in a qutrit based on a flux-type superconducting device. One of the control protocols that we implement relies on concomitantly driving multiple transitions and makes use of ac-Stark shift corrections. In the second half of the talk, I will present a proposal for a two-qutrit gate based on parametric activated gates, in an implementation based on two transmon-type superconducting devices.

17.10 - 17.50: Susanne Yelin

Title: Quantum chemistry with a quantum computer

Abstract: Simulations of quantum chemistry and quantum materials are believed to be among the most important potential applications of quantum information processors, but realizing practical quantum advantage for such problems is challenging. We introduce a simulation framework for strongly correlated quantum systems that can be represented by model spin Hamiltonians. Our approach leverages, in addition to an effective many-qubit-to-qudit transformation, reconfigurable qubit architectures to programmably simulate real-time dynamics and introduces an algorithm for extracting chemically relevant spectral properties via classical co-processing of quantum measurement results. We develop a digital-analog simulation toolbox for efficient Hamiltonian time evolution utilizing digital Floquet engineering and hardware-optimized multi-qubit operations to accurately realize complex spin-spin interactions, and as an example present an implementation proposal based on Rydberg atom arrays. Then, we show how detailed spectral and other relevant chemical information can be extracted from these dynamics through snapshot measurements and single-ancilla control, enabling the evaluation of excitation energies and finite-temperature susceptibilities from a single-dataset. To illustrate the approach, we show how this method can be used to compute key properties of a polynuclear transition-metal catalyst and 2D magnetic materials.

Abstracts

Workshop Day 2: Wednesday 10 July
@ Institute for Quantum Computing

09.20 - 10.00: Eleanor Crane
Title: Hybrid Oscillator-Qubit Quantum Processors: Simulating Fermions, Bosons, and Gauge Fields
Abstract: Finding a scalable and universal framework for quantum simulation of strongly correlated fermions and bosons is an important goal for fields ranging from materials science to high-energy physics. While digital qubit-only quantum computers in principle offer such universality, the overhead encountered in mapping bosons to qubits, particularly in spatial dimension D>1, renders this endeavour extremely challenging to implement in practice. Here, we develop an approach to simulate bosonic matter, fermionic matter, and Abelian gauge fields in D=2 on near-term hybrid oscillator-qubit quantum processors. This approach avoids the boson-to-qubit overhead altogether, which makes the process viable on NISQ era hybrid devices for modestly large boson number cutoffs. We present novel compilation strategies, enabling exact bosonic density-density or parity-dependent interaction terms, and non-local qubit coupling terms including a novel compilation of the U(1) magnetic field term that would be challenging to implement in qubit-only NISQ hardware. We show how our compilation strategies can be used to study both dynamics and ground states by introducing a hybrid oscillator-qubit variational quantum eigensolver. To illustrate the promise of our compilation methods we numerically simulate experiments for the Z2 and the U(1) quantum link model including the dominant sources of hardware error for superconducting qubits coupled to high-Q cavities. We show that near-term devices can observe signatures of phase transitions in these models by developing measurement techniques for non-local observables such as string-order correlators and the superfluid stiffness. Finally, we compare the gate complexity of all-qubit and hybrid oscillator-qubit hardware for Trotter-based simulations of lattice gauge theories, finding a prefactor advantage of our approach of up to three orders of magnitude. Our work opens a path toward using oscillator-qubit hardware such as can be found in superconducting, trapped ion, and neutral atom platforms. Altogether, this work illustrates the potential of, and provides an explicit manual for, using hybrid oscillator-qubit hardware for simulating models containing strongly correlated fermions and bosons and gauge fields.

10.00 - 10.40: Sabre Kais
Title: Simulation of Chemical Reactions on a Quantum Computer
Abstract: In this talk , I will present a quantum computing algorithm for the calculation of scattering matrix elements. In this approach, we employ the time-dependent method based on the Møller operator formulation where the S-matrix element between the respective reactant and product channels is determined through the time correlation function of the reactant and product Møller wave packets. We successfully apply our quantum algorithm the colinear hydrogen exchange reaction. Finally, I will discuss how to generalize this algorithm to qudit space.

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11.10 – 11.50: Crystal Senko
Title: High-dimensional qudit control in trapped ions for quantum computing and quantum simulation
Abstract: In this talk, I will present ongoing experimental work on the preparation, readout, and control of large qudits (up to d=25 levels) encoded in Ba-137+ ions. I will discuss experimental challenges in the simultaneous control of 9+ quantum states, and present recent results on high-fidelity state preparation and measurement (SPAM) of a 25-level qudit. I will also discuss our preliminary work on control and diagnostics of coherent superposition states, which we anticipate to be a key prerequisite to use these high-dimensional quantum resources for computation and quantum simulation. As an outlook, I will highlight some open questions relevant to the further development of qudit-based quantum processors.

11.50 - 12.30: Ashok Ajoy
Title: New advances towards deployable quantum sensors
Abstract: TBA

13.40 - 14.10: Jacqui Romero
Title: Towards qudit quantum computation
Abstract: In this talk, I will give a brief introduction to photonic qudits, focusing on the transverse mode of photons. I will present some of our current efforts in qudit quantum information processing, both in free space and on-chip. Techniques based on design by specification has allowed us to design qudit gates in free-space, and observe Hong-Ou-Mandel interference on-chip. These techniques (hopefully) spur some inspiration for realising photonic qudit quantum computation in the future.

14.10 - 14.50: Joe Emerson
Title: Hardware and Software Development Tools for Qudit Experiments
Abstract: TBA

15.20 - 16.00: Lia Yeh
Title: TBA
Abstract: This talk is about two papers. In the first paper, we introduce the qudit ZH-calculus and generalize all the qubit phase-free ZH-calculus rules to qudits of prime dimension d. We prove that the phase-free qudit ZH-calculus is universal for matrices over the ring Z[e^2(pi)i/d]. We define the qudit Toffoli+Hadamard gate set and justify this definition, by constructing all d-ary classical reversible circuits from just the Toffoli gate, and by showing that Toffoli+Hadamard is moreover also approximately universal for quantum computation in any odd prime qudit dimension. Furthermore, we show that as is the case for qubits, qudit phase-free ZH-calculus diagrams correspond precisely to circuits allowing post-selections over this Toffoli+Hadamard gate set.

In the second paper, we first establish exact synthesis for the qutrit Toffoli+Hadamard gate set: Every circuit over that gate set has matrix entries in the ring Z[e^2(pi)i/d], and every power of 3 sized unitary matrix with entries in that ring can always be compiled to a circuit over that gate set. We then define a hierarchy of qutrit gate sets called the Clifford-cyclotomic gate sets, of which Toffoli+Hadamard is the base case and Clifford+T is the gate set one higher than it in the hierarchy. Through catalytic embeddings, we extend our Toffoli+Hadamard result to establish exact synthesis for all gate sets in the Clifford-cyclotomic hierarchy.