Titles and abstracts of speakers, WACQT workshop Quantum Technology

26 April: Quantum Computing and Quantum Simulation

"Simulating quantum computers"

Kristel Michielsen

Abstract:

Quantum computing promises unprecedented possibilities for important computing tasks such as quantum simulations in chemistry and materials science or optimization and machine learning. With this potential, quantum computing is increasingly attracting interest from industry and scientific communities that use high performance computing (HPC) for their applications. These pilot users are primarily interested in testing whether available quantum computers today or in the foreseeable future are suitable for simulating increasingly complex systems, analyzing large data sets using machine learning methods or performing the hardest optimization task.

Access to quantum computer emulators running on HPC systems and to quantum computing systems at the forefront of development is the prerequisite for testing, benchmarking, algorithm and use case design activities, and first serious applications in scientific and engineering challenges.

Benchmarking quantum computers and algorithms requires emulators that can efficiently utilize the architecture of present-day supercomputers. As the simulation of universal quantum computers requires a large number of matrix-vector updates, most of which are 2-component and 4-component tensor operations, the task of simulating quantum computers is an ideal candidate to profit from recent developments in the GPU industry. We present benchmarks of some of the most powerful supercomputers using the Jülich universal quantum computer simulator (JUQCS). In addition, we show some benchmarks using other simulators emulating transmon quantum computers.

"Emitting and Absorbing a Directional Microwave Photon with Waveguide Quantum Electrodynamics"

Aziza Almanakly

Abstract:

Routing quantum information between non-local computational nodes is a foundation for extensible networks of quantum processors. Quantum information transfer between arbitrary nodes is generally mediated either by photons that propagate between them, or by resonantly coupling nearby nodes. The utility is determined by the type of emitter, propagation channel, and receiver. Conventional approaches involving propagating microwave photons have limited fidelity due to photon loss and are often unidirectional, whereas architectures that use direct resonant coupling are bidirectional in principle, but can generally accommodate only a few local nodes. In this work, we develop a quantum interconnect composed of an emitter, receiver, and propagation channel that circumvent issues of prior work. We have demonstrated high-fidelity directional microwave photon emission using an artificial molecule comprising two superconducting qubits strongly coupled to a bidirectional waveguide. Quantum interference between the photon emission pathways from the molecule generates single photons that selectively propagate in a chosen

direction. By emitting time-symmetric photons from one module, we operate another identical module tiled along the same waveguide as an absorber of directional microwave photons, developing an interconnect capable of hosting remote entanglement for extensible quantum networks.

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"Realization of an error-corrected quantum memory beyond break-even”

Alec Eickbusch

Abstract:

The past four years have seen rapid experimental progress in the realization of bosonic quantum error correction (QEC) using the code proposed in 2001 by Gottesman, Kitaev, and Preskill (GKP) in which logical states are encoded as grid states of an oscillator [1]. In this talk I will present the key experimental milestones in this area demonstrated by our lab at Yale, starting with the first experimental realization of QEC with the GKP code in 2020 [2]. Next, I will briefly discuss how we used insights from this experiment to realize fast universal control of an oscillator with weak dispersive coupling to a qubit, enabling the rapid unitary preparation of GKP states [3]. Finally, I will review our recent experiment to optimize the QEC protocol and realize an error-corrected quantum memory with coherence beyond break-even [4,5].

[1] Gottesman, Kitaev, Preskill, PRA 2001; [2] Campagne-Ibarcq*, Eickbusch*, Touzard* et al. Nature 2020; [3] Eickbusch et al. Nature Physics 2022; [4] Royer, Singh, Girvin, PRL 2020 [5] Sivak et al. Nature, 2023"

"Characterization of fabrication methods to reach high coherence superconducting quantum circuits”

Leon Koch

Abstract:

The fabrication of superconducting qubits and resonators with long coherence times and high quality factors is an important milestone on the way towards useful quantum processors. Although significant improvements in coherence time have been made over the last years, reaching qubit lifetimes well beyond 100 µs involves careful investigation of all fabrication steps. Here, we demonstrate that such high device qualities can be achieved by a combination of substrate cleaning, etching optimization and post-process sample cleaning. We optimize sputtering, etching and metal interconnecting processes. Thereby, we reach quality factors well above 3x10^6 for thin-film niobium CPW resonators and qubit lifetimes of over 300 µs. "

"Unravelling the Entanglement Structure of Correlated Quantum Matter”

Christian Kokail

Abstract:

Entanglement is the crucial ingredient that sets apart the quantum world from its classical counterpart, and characterizing and quantifying Entanglement represents a challenging task in today’s era of NISQ devices. In this talk, I will represent a novel approach in understanding the entanglement structure of quantum many-body states in terms of the so-called Entanglement Hamiltonian (EH). In many relevant situations, the EH exhibits a remarkable local structure, facilitating the sample-efficient reconstruction of the reduced density matrix. I will report on an experimental collaboration in which we utilize this approach to analyze the entanglement structure of quantum many-body states in quantum simulation experiments encompassing up to 51 ions. For subregions up to a size of 20 qubits, our approach recovers the spatial shape of the EH, allowing us for the first time to detect (and also verify) generic predictions of conformal field theory and relativistic quantum field theory in quantum simulation experiments. Our approach is universally applicable among all quantum simulation platforms and adds new insights into the Entanglement features with respect to the geometry and topology of subregions.

"Combining machine-learning characterization and quantum optimal control to improve superconducting qubit operations”

Élie Genois

Abstract:

Quantum optimal control theory offers a powerful toolbox to design pulse shapes that can realize, in numerical simulations, desired quantum operations with extremely high fidelity. When implementing these pulses in practice, however, the benefit of using optimal pulses over simple analytical forms is often greatly reduced. A significant part of this discrepancy can be attributed to failures of the numerical model to precisely capture the complete quantum dynamics generated by the control electronics. Here, we address this issue directly by building a framework where we break down the problem of realizing high-fidelity quantum operations into two parts. First, we use physics-inspired machine learning to infer an accurate model of the dynamics from experimental data. Second, we use such a trained numerical model in combination with state-of-the-art quantum optimal control to find pulse shapes that realize quantum gates with maximal accuracy given our experimental constraints. Using numerical simulations, we show the feasibility of learning from realistically available data to accurately characterize qubit dynamics and to discover high-fidelity arbitrary single-qubit gates. We then demonstrate our framework in an experimental setting by optimizing the Clifford gate set of a superconducting transmon qubit.

"Beyond standard control of superconducting qubits”

Stefan Filipp

Abstract:

Recent years have witnessed a rapid development of quantum technologies culminating in the realization of first quantum computer prototypes. Still, to render today’s quantum processors practically useful we must tackle numerous challenges to both enhance the coherence and the control capabilities of a large number of qubits. Along these lines, we explore superconducting qubit architectures that contain 'hidden' qubits, which are not directly addressable. We have experimentally demonstrated full control and measurement capabilities of such a hidden qubit and explored the impact of such restricted control capabilities on the performance of specific qubit coupling networks. To enhance the connectivity of qubit arrays and the efficiency of generating entanglement we are investigating multi-qubit operations based on simultaneously activated local interactions. In this presentation I will demonstrate a fractional state transfer protocol on a chain of superconducting qubits interacting via tunable couplers and discuss its potential use case for quantum simulations, multi-qubit gates and parity readout. These activities are part of the newly formed Munich Quantum Valley, a cross-disciplinary initiative to realize a full-stack quantum computer.

"Implementing the dual-rail encoding with superconducting cavities”

James Teoh

Abstract:

The design of quantum hardware that reduces and mitigates errors is essential for practical quantum error correction (QEC) and useful quantum computation. To this end, we introduce the circuit-QED dual-rail qubit in which our physical qubit is encoded in the single-photon subspace of two superconducting cavities. The dominant photon loss errors can be detected and converted into erasure errors, which are in general much easier to correct. In contrast to linear optics, a circuit-QED implementation of the dual-rail code offers completely new capabilities. Using just one additional transmon ancilla per dual-rail qubit, we describe how to perform a gate-based set of universal operations that includes state preparation, logical readout, and parametrizable single and two-qubit gates. Moreover, first-order hardware errors in the cavities and the transmon can be detected and converted to erasure errors in all operations, leaving background Pauli errors that are orders of magnitude smaller. Hence, the dual-rail cavity qubit exhibits a favorable hierarchy of error rates and is expected to perform well below the relevant QEC thresholds with today’s coherence times.

"Gradient-Descent Quantum Process Tomography by Learning Kraus Operators”

Shahnawaz Ahmed

Abstract:

In this talk, we will present a data-driven approach for performing quantum process tomography (QPT) on both discrete and continuous variable quantum systems. Our method involves learning a process representation using Kraus operators, which ensures the reconstructed process is completely positive. To make the process trace preserving, we use a constrained gradient-descent approach on the Stiefel manifold during optimization. Our approach uses a few Kraus operators to avoid direct estimation of large process matrices, making it suitable for low-rank quantum processes. We will show that our approach matches the performance of both compressed-sensing and projected least-squares QPT in benchmarks with two-qubit random processes, but shines by combining the best features of these two methods. We will also demonstrate that our approach works for larger system sizes, up to at least five qubits. We envision that our data-driven approach can become a practical tool that greatly reduces the cost and computational effort for QPT in intermediate-scale quantum systems.

“Probing entanglement across the energy spectrum of a hard-core Bose-Hubbard lattice”

Amir Karamlou

Abstract:

Entanglement and its propagation are central to understanding extensive physical properties in quantum systems. Within closed quantum many-body systems, entanglement is believed to yield emergent thermodynamic behavior, yet a universal understanding remains challenging due to the non-integrability and computational intractability of these systems at scale.

Quantum hardware platforms provide a means to study the formation and scaling of entanglement in interacting many-body systems. Here, we use a fully controllable 4×4 array of superconducting qubits to emulate a two-dimensional hard-core Bose-Hubbard lattice.

We generate superposition states by simultaneously driving all lattice sites and extract correlation lengths and entanglement entropy across its many-body energy spectrum.

We observe a crossover from area-law-like entanglement scaling for states near the edges of the spectrum to volume-law scaling at its center.

"Observation of Josephson Harmonics in Tunnel Junctions”

Dennis Willsch

Abstract:

The Josephson effect is the keystone of quantum computing with superconducting hardware. In this talk, I will show that the celebrated sin(phi) Josephson relation fails to fully describe the measured energy spectra of many transmon samples. While the microscopic theory of Josephson junctions contains higher harmonics sin(2*phi), sin(3*phi), ..., these have generally been considered negligible in tunnel junctions. However, this assumption is unjustified due to the non-uniformity of the commonly used AlOx tunnel barriers, which can cause high-transparency conduction channels. Indeed, by including the Josephson harmonics in the transmon Hamiltonian, we can greatly improve the agreement between computed and measured energy spectra. The observation of Josephson harmonics in tunnel junctions prompts a reevaluation of our theoretical models for superconducting hardware.

“Characterizing the performance of trapped-ion quantum error correction circuits using realistic microscopic noise models”

Andrea Rodriguez-Blanco

Abstract:

Regardless of the qubit encoding and the specific quantum error correcting. (QEC) code, errors in qubit control operation still limit the successful implementation of fault-tolerant (FT) quantum QEC protocols. From current state-of-the-art experiments, one can note that errors on two-qubit entangling gates are still the major bottleneck to obtaining better pseudo-thresholds. Consequently, understanding the principal physical noise mechanism of two-qubit gates is necessary to achieve a successful implementation of fault-tolerant quantum error correction. Here, following the results from PRXQuantum.2.020304 and its experimental realization

in PhysRevX.12.011032, we were drawn to assess the performance of parity-check QEC circuits in the presence of a more realistic noise model. We present a detailed microscopic error model to estimate the average gate infidelity of a two-qubit light shift entangling gate, a common gate used in trapped ion platforms. We, first, analytically derive leading-error contributions in terms of microscopic and experimental parameters and, then, we feed the realistic microscopic entangling gate infidelity into effective noise models for the light shift gates. Hence, the dynamical quantum map we use to discuss the noisy evolution of imperfect entangling gates in the parity-check QEC circuits has error rates that connect to realistic microscopic calculations, rather than giving them arbitrary values from 0 to 1.

We then characterize the performance of non-FT and flag-based FT parity-check readout circuits in terms of their ability to generate genuine maximally entangled (GME) states using experimentally friendly entanglement witnesses.

"Emulating two qubits with a four-level transmon qudit for variational quantum algorithms”

Shuxiang Cao

Abstract:

Using quantum systems with more than two levels, or qudits, can scale the computation space of quantum processors more efficiently than using qubits, which may offer an easier physical implementation for larger Hilbert spaces. However, individual qudits may exhibit larger noise, and algorithms designed for qubits require to be recompiled to qudit algorithms for execution. In this work, we implemented a two-qubit emulator using a 4-level superconducting transmon qudit for variational quantum algorithm applications and analyzed its noise model. The major source of error for the variational algorithm was readout misclassification error and amplitude damping. To improve the accuracy of the results, we applied error-mitigation techniques to reduce the effects of the misclassification and qudit decay event. The final predicted energy value is within the range of chemical accuracy. Our work demonstrates that qudits are a practical alternative to qubits for variational algorithms.

"Transmon qubit readout fidelity at the threshold for quantum error correction without a quantum-limited amplifier”

Liangyu Chen

Abstract:

High-fidelity and rapid readout of a qubit state is key to quantum computing and communication, and it is a prerequisite for quantum error correction. We present a readout scheme for superconducting qubits that combines two microwave techniques: applying a shelving technique to the qubit that reduces the contribution of decay error during readout, and a two-tone excitation of the readout resonator to distinguish among qubit populations in higher energy levels. Using a machine-learning algorithm to post-process the two-tone measurement results further improves the qubit-state assignment fidelity. We perform single-shot frequency-multiplexed qubit readout, with a 140 ns readout time, and demonstrate 99.5% assignment fidelity for two-state readout and 96.9% for three-state readout–without using a quantum-limited amplifier.

27 April: Quantum Sensing and Quantum Communication

“Parameter estimation with light, from the quantum Fisher information to experimental implementations”

Nicolas Treps

"Electron spin resonance (ESR) with single spin addressability"

Zhiren Wang

Abstract:

Electron spin resonance (ESR) with single spin addressability is an approach to characterize paramagnetic species and gives coherent manipulation of the spins. This goal has been reached in various systems or techniques, such as gate-defined quantum dots, spin-dependent photoluminescence and scanning-probe techniques. However, these approaches require specific systems or restrict themselves to small detection volume. Therefore, operational and universal single spin detection remains a challenge. Here, we demonstrate single electron spin resonance by spin fluorescence detection with a superconducting-qubit-based single microwave photon detector at cryogenic temperature. We couple individual paramagnetic erbium ions in a scheelite crystal to a high-quality factor superconducting resonator to enhance their radiative decay rate. By counting the spontaneously emitted photons from ions, we resolve their ESR spectrum down to single impurity level. In one second integration time of the detection, we reach a signal-to-noise ratio of 1.45. The observed photon anti-bunching in the spin emission proves that the fluorescence signal comes from single emitters. Our results pave the way for practical ESR spectroscopy of arbitrary paramagnetic species with single spin resolution and it may also find potential applications for quantum computing.

"Title - Squeezed light: generation and application to gravitational wave detection”

Vaishali Adya

Abstract:

Squeezed light technology has improved the sensitivity of precision measurement experiments ranging from gravitational wave detection to microscopy. Right from its conception in 1950’s its implementation in LIGO, squeezed light generation has come a long way. In this talk, I will discuss the upgrades made to the detectors and mainly the squeezed light system which will increase the astrophysical reach of the detectors when they come online for the next observing run towards the end of May.

"Experimental separation estimation between two optical point sources reaching the (quantum) Cramér-Rao bound”

Clémentine Rouvière

Abstract:

We experimentally implement the separation estimation between to incoherent sources. Our method, relying on spatial-mode demultiplexing and intensity measurements, saturates the Cramér-Rao bound, with a 30nm-sensitivity, corresponding to a five orders of magnitude gain compared to the beam size.

"Quantum quenches for enhancing qubit-based noise spectroscopy”

Yuxin Wang

Abstract:

Qubit-based noise spectroscopy (QNS) techniques, where the dephasing of a probe qubit is exploited to study a system of interest, underlie some of the most common quantum sensing and noise characterization protocols. They have a variety of applications, ranging from designing effective quantum control protocols to investigating properties (phase transitions, thermodynamics, etc.) of quantum many-body systems. In this talk, I will discuss a simple and powerful strategy for enhancing standard QNS methods, making use of a quantum quench that is inadvertently induced on the probed system in a standard sensing protocol. Those quenches lead to observable changes in the sensor qubit evolution, which allow one to extract environmental response properties. The quench-based QNS techniques thus enable a host of sensing protocols including direct measurement of bath temperature and detection of non-thermal equilibrium states. While our ideas are readily applicable to a range of sensing platforms, as a concrete example, I will also describe recent experimental implementations using nitrogen-vacancy (NV) centers in diamond.

"Programmable distribution of multi-qubit entanglement in dual-rail waveguide QED"

Joan Agustí

Abstract:

We investigate the autonomous generation of multi-partite entangled states in a dual-rail waveguide QED configuration. Here, qubits arranged along two separated photonic waveguides are illuminated by the output of a nondegenerate parametric amplifier, which drives them into a strongly correlated steady state. We show that in this setup, there exists a large family of pure steady states, for which the connectivity and the degree of multi-qubit entanglement can be selectively adjusted by simply changing the applied pattern of qubit-photon detunings. This offers intriguing new possibilities for distributing ready-to-use multi-partite entangled states across large quantum networks, which do not require any precise pulse control and rely on Gaussian entanglement sources only.

"Ultrasensitive calorimetric detection in superconducting quantum circuits”

Bayan Karimi

Abstract:

We demonstrate experimentally an ultra-sensitive calorimeter formed of an electronic absorber coupled to a phonon bath, which reaches the noise level dictated by the fundamental thermal fluctuations [1]. A scheme of coupling a superconducting qubit to this detector is presented and we conclude that it has sufficient signal-to-noise ratio (SNR) to measure a microwave photon emitted by it [2,3,4]. The calorimeter admits photons of essentially any energy and it does not require a reset. This detection scheme is suitable for observing quantum phase slips in a Josephson junction, as was demonstrated in a recent experiment [5], and currently we are performing preliminary measurements on the proposed qubit calorimetry.

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