QI 3: Quantum Simulation

Time: Monday 15:00–18:30 Location: BEY/0137

QI 3.1 Mon 15:00 BEY/0137

Real-Time Dynamics in a (2+1)-D Gauge Theory: The Stringy Nature on a Superconducting Quantum Simulator — Jesús Cobos[1], Joana Fraxanet[2], César Benito[3], Francesco di Marcantonio[1], Pedro Rivero[2], Kornél Kapás[4], •Miklós Antal Werner[4], Örs Legeza[4,5,6,7], Alejandro Bermudez[3], and Enrique Rico[1,8,9,10] — [1]EHU QC, Bilbao, Spain — [2]IBM Quantum, New York, USA — [3]UAM-CSIC, Madrid, Spain — [4]Wigner RCP, Budapest, Hungary — [5]Dynaflex LTD, Budapest, Hungary — [6]TUM IAS, Garching, Germany — [7]Parmenides St., Pöcking, Germany — [8]DIPC, San Sebastián, Spain — [9]IKERBASQUE, Bilbao, Spain — [10]CERN, Geneva, Switzerland

We probe string modes of motion with dynamical matter in a digital quantum simulation of the $\mathbb{Z}_2$-Higgs model with an optimized embedding into a heavy-hex organized superconducting quantum processor with up to 144 qubits. Using local gauge symmetries, we implement various error suppression, mitigation, and correction strategies to enable high control of electric strings connecting dynamical charges and to observe longitudinal oscillations and transverse bending at the endpoints of the string, which are precursors to hadronization and rotational spectra of mesons. To validate our error-aware protocols, we employ extensive tensor network simulations: the relevant parameter regimes of the model are determined by large-scale DMRG simulations. The dynamics are classically simulated by the basis update and Galerkin (BUG) method, and the agreement with hardware results is remarkable.

QI 3.2 Mon 15:15 BEY/0137

Braiding of Majorana zero modes on the digital IBM quantum processor — •Stefan Schmitz[1,2], Kevin Lively[3], Maike Drieb-Schön[4], Tim Bode[1], Benedikt Fauseweh[3,5], and Dmitry Bagrets[1,2] — [1]Peter Grünberg Institute, Quantum Computing Analytics (PGI-12), Forschungszentrum Jülich, 52425 Jülich, Germany — [2]Institute for Theoretical Physics, University of Cologne, 50937 Cologne, Germany — [3]Institute for Software Technology, German Aerospace Center (DLR), 51147 Cologne, Germany — [4]Institute for Theoretical Physics, University of Innsbruck, 6020 Innsbruck, Austria — [5]Department of Physics, TU Dortmund University, 44227 Dortmund, Germany

The search for elusive Majorana fermions in solid-state devices has occupied the scientific community for more than a decade. Their unambiguous detection is expected to rely on a braiding protocol that can verify their non-Abelian statistics. We have emulated one variant of this protocol using digital quantum simulations performed on IBM quantum processors. Remarkably, only 12 Trotter steps are sufficient to reproduce a theoretically predicted Majorana braiding operation with a fidelity exceeding 99.9 % in the absence of decoherence and noise. In experiment, this upper bound can not be reached due to the lack of topological protection for the virtual Majoranas. However, we show that applying error mitigation techniques can restore experimental fidelity to values close to the ideal limit.

QI 3.3 Mon 15:30 BEY/0137

How compactness curbs entanglement growth in bosonic systems — •Stefan Aimet[1], Philipp Schmoll[1], Jens Eisert[1], and Spyros Sotiriadis[2] — [1]Freie Universität Berlin, Dahlem Center for Complex Quantum Systems and Institut für Theoretische Physik, 14195 Berlin, Germany — [2]Institute of Theoretical and Computational Physics, University of Crete, 71003 Heraklion, Greece

Zero modes, degrees of freedom with vanishing frequency, play a crucial role in the non-equilibrium dynamics of bosonic systems. In Gaussian models, such zero modes are known to drive unbounded, logarithmic growth of entanglement entropy. We show that this divergence is not an inherent feature of zero modes per se, but arises only for non-compact zero modes whose continuous spectrum and non-normalisable eigenstates allow unbounded position-space spreading and momentum-space dephasing. By contrast, compact zero modes occurring in compact bosonic systems behave fundamentally differently: spreading and dephasing are eventually halted, and compactness caps the entanglement entropy at a finite value. We demonstrate this mechanism using a minimal toy model comparing two coupled harmonic oscillators with two coupled quantum rotors, and show that the same underlying physics carries over to many-body settings by comparing an N-site compact rotor chain with the non-compact harmonic chain. Finally, we relate these insights to ultracold-atom realisations of compact quantum field theories, clarifying when the compact free boson (Tomonaga-Luttinger liquid) description is required and when the commonly used non-compact massless Klein-Gordon model fails.

QI 3.4 Mon 15:45 BEY/0137

A Parametrically-Driven High-Q Multimode Cavity for Analog Quantum Simulations — •Johannes Schading[1], Ian Yang[1], Joao C. Pinto Barros[2], Thea Budde[2], Raquel Garcia-Belles[3], Alexander Anferov[3], Yiwen Chu[3], Marina Marinkovic[2], and Alexander Grimm[1] — [1]Bosonic Quantum Information Group (LNQ/CPS), Paul Scherrer Institute, Switzerland — [2]High Performance Computational Physics Group, ETH Zürich, Switzerland — [3]Hybrid Quantum Systems Group, ETH Zürich, Switzerland

Analog quantum simulations offer a powerful route to study real-time dynamics in systems such as lattice gauge theories or quantum synchronization of nonlinear oscillators. However, these simulations require interaction strengths to exceed decoherence rates by a large margin. Our approach to address this challenge is to encode the system degrees of freedom in high-Q bosonic modes and activating strong parametric interactions in an all-to-all-connected multimode architecture coupled to a superconducting qubit. By applying a microwave drive, we use a qubit-mediated fourth-order parametric process to realize a three-bosonic-mode interaction with a hopping rate of $J/2\pi > 50$ kHz, significantly larger than typical decay rates in high-purity aluminum cavities [1]. Our multimode architecture allows for in-situ connectivity that enables simulations of high-dimensional systems, such as a (2+1)D lattice formulation of the Schwinger model. In this talk, I will discuss our progress towards implementing analog quantum simulations with parametrically-activated bosonic-mode interactions.

[1] Chakram, S. *et al.* *Physical Review Letters* **127**, 107701 (2021).

QI 3.5 Mon 16:00 BEY/0137

Effective Hamiltonians for Measurement Protocols in Quantum Circuits — •Manuel Freudig[1], Davide Bincoletto[2], Francesco Diotallevi[1], Leander Reascos[1], Mónica Benito[1], and Jakob Kottmann[2] — [1]Institute of Physics, University of Augsburg, Augsburg, Germany — [2]Institute for Computer Science, University of Augsburg, Augsburg, Germany

A significant drawback for the realization of Variational Quantum Eigensolvers (VQEs), is the overhead due to measurement repetitions. Addressing this bottleneck, an iterative measurement protocol, designed for molecular Hamiltonians, was introduced [1]. It relies on cheaply measuring commuting groups of operators, while the residual (non-commuting) elements are grouped in a different basis and then measured. Our work proposes an enhanced measurement strategy by integrating the iterative measurement protocol [1] with perturbative and non-perturbative techniques for the derivation of effective Hamiltonians [2,3]. This combination aims to further reduce measurement overhead and increase the accuracy of the approximated expectation value, providing a more viable path for practical VQE implementations.

[1] Bincoletto, D.; Kottmann, J. S.; arXiv:2504.03019. [2] Li, B.; Calarco, T.; Motzoi, F.; PRX Quantum 3, 030313. [3] Schrieffer, J. R.; Wolff, P. A.; Phys. Rev. 149, 491-492.

QI 3.6 Mon 16:15 BEY/0137

Hamiltonian simulation with explicit formulas for Digital-Analog Quantum Computing — Mikel Garcia de Andoin[1,2], Thorge Müller[3], and •Gonzalo Camacho[3] — [1]University of the Basque Country UPV/EHU, Leioa, Spain — [2]EHU Quantum Center, Leioa, Spain — [3]Deutsches Zentrum für Luft- und Raumfahrt (DLR), Köln, Germany

In Hamiltonian simulation, modifying a given source Hamiltonian is often required to engineer a desired target Hamiltonian. In this work, we provide an exact solution for the problem of expressing arbitrary target two-body Hamiltonians as the sum of local unitary transformations of an arbitrary source Ising Hamiltonian, with the total number of required terms being at most quadratic in system size. This allows us to design an efficient digital-analog compilation protocol for Hamiltonian simulation that avoids employing numerical optimization over a large parameter space, minimizes computational resources and allows for further scaling.

30min. break

QI 3.7 Mon 17:00 BEY/0137

Barren-plateau free variational quantum simulation of Z2 lattice gauge theories — •Fariha Azad[1], Matteo Inajetovic[1], Stefan Kühn[2], and Anna Pappa[1] — [1]Electrical Engineering and Computer Science Department, Technische Universität Berlin, 10587 Berlin, Germany — [2]Deutsches Elektronen-Synchrotron DESY, Platanenallee 6, 15738 Zeuthen, Germany

In this work, we design a variational quantum eigensolver (VQE) suitable for investigating ground states and static string breaking in a Z2 lattice gauge theory (LGT). We consider a two-leg ladder lattice with Kogut-Susskind staggered fermions and verify the results of the VQE simulations using tensor network methods. We find that for varying Hamiltonian parameter regimes and in the presence of external charges, the VQE is able to arrive at the gauge-invariant ground state without explicitly enforcing gauge invariance through penalty terms. Additionally, experiments showing string breaking are performed on the IBM quantum platform. Thus, VQEs are seen to be a promising tool for Z2 LGTs, and could serve as a stepping stone toward studies of other gauge groups. We find that the scaling of gradients with the number of qubits is favorable for avoiding barren plateaus. Furthermore, strategies that avoid barren plateaus arise naturally as features of LGTs, such as choosing the initialization by setting the Gauss law sector and restricting the Hilbert space to the gauge-invariant subspace.

QI 3.8 Mon 17:15 BEY/0137

Efficient Quantum and Classical Simulation of the Non-Uniform Wave Equation — •Kevin Lively, Vittorio Pagni, and Gonzalo Camacho — Deutsches Zentrum für Luft- und Raumfahrt, Quantum Computing Applications, Sankt Augustin

We present an efficient algorithm based on the construction of a unitary quantum circuit for simulating the non-uniform wave equation in one, two or three dimensions. We utilize the first-order-in-time-derivative form of the wave equation alongside Pauli four-vectors to embed and manipulate vector quantities in a language which translates naturally to quantum simulation. We exploit this to create an efficient quantum-inspired classical tensor-network algorithm to inject and propagate waveforms through inhomogeneous media far beyond the memory limitations of naive finite difference methods. We explore applications of this algorithm in real world data-sets of complex media.

QI 3.9 Mon 17:30 BEY/0137

Quantum Simulation of Electron-Phonon Interactions in Circuit QED — •Riccardo Roma[1,2], Tim Bode[1], Dmitriy S. Shapiro[1], Alessandro Ciani[1], Dmitry Bagrets[1,3], and Frank Wilhelm-Mauch[1,2] — [1]Institute for Quantum Computing Analytics (PGI-12), Forschungszentrum Jülich, 52425 Jülich, Germany — [2]Theoretical Physics, Saarland University, 66123 Saarbrücken, Germany — [3]Institute for Theoretical Physics, University of Cologne, 50937 Cologne, Germany

Electron-phonon interaction is a fundamental process in condensed-matter physics, responsible for a variety of phenomena ranging from polaron formation in semiconductors and molecules to charge-density waves, (high-temperature) superconductivity or the Hubbard-Holstein (HH) and the Yukawa-Sachdev-Ye-Kitaev (YSYK) models.

Leveraging physical resonators for emulating bosonic degrees of freedom allows to circumvent the considerable overhead associated with their encoding in qubits. It also avoids the necessity of truncating the bosonic Fock space, which is an inherent limitation of current qubit encodings.

We extend the standard gate set available for superconducting qubits by entangling gates between a transmon and a microwave resonator, showing how this can be achieved experimentally via flux tuning or microwave driving. We then derive the digital simulation circuits for the HH and YSYK models. Our work concludes with a minimal electron-phonon model for which we demonstrate a Dicke-type superradiant transition that is robust to noise and thus experimentally feasible.

QI 3.10 Mon 17:45 BEY/0137

Discrete local dynamics in globally driven dual-species Rydberg atom arrays — Francesco Cesa[3,4], Andrea di Fini[1,2], •David Korbany[1,2], Roberto Tricarico[3,4], Hannes Pichler[3,4], Hannes Bernien[3,5,6], and Lorenzo Piroli[1,2] — [1]DIFA, Universit'a di Bologna — [2]INFN, Sezione di Bologna — [3]IQOQI Innsbruck — [4]Institute for Theoretical Physics, University of Innsbruck — [5]Pritzker School of Molecular Engineering, University of Chicago — [6]Institute for Experimental Physics, University of Innsbruck

We present a simple construction to implement a family of one- and two-dimensional discrete dynamics using dual-species Rydberg atom arrays. The discrete dynamics that we consider are special examples of quantum cellular automata (QCA) and include the exact Floquet dynamics of the kicked Ising model, as well as the Trotterized evolution of translation-invariant nearest-neighbor Hamiltonians. In our scheme, one of the two species of atoms represents the physical qubits, while the other species plays an auxiliary role, mediating the interactions. Our construction only requires global driving, with no local addressing of the qubits, and assumes an ideal blockade regime. Importantly, when the inter-species interactions are dominant over the intra-species one, we give a simple argument showing that, both in the one- and two-dimensional case, the deviations from the ideal blockade regime are at least as small as for established single-species implementations in one-dimensional arrays. Finally, we illustrate applications of our constructions in the study of chaotic features of QCA dynamics. Our results may be relevant for near-term experimental implementations.

QI 3.11 Mon 18:00 BEY/0137

Extracting transport properties using zero noise extrapolations of noisy quantum dynamics — •Hansveer Singh[1], Pieter Claeys[1], Sarang Gopalakrishnan[2], and Anushya Chandran[3] — [1]Max Planck Institute for the Physics of Complex Systems, Dresden, DE — [2]Princeton University, Princeton, New Jersey USA — [3]Boston University, Boston, Massachusetts, USA

We examine extrapolating transport coefficients of quantum systems subjected to weak noise. Though noise generally breaks conservation laws of a quantum system, we show for weak noise strengths it is still possible to define an effective notion of transport. For chaotic diffusive quantum systems, we provide a protocol to extrapolate diffusion constants and argue that the effective diffusion constant in the weak noise limit can be decomposed into two parts: an analytic function of the noise strength and a function determined by non-linear corrections to diffusive hydrodynamics. We support our findings with tensor network simulations of a dissipative version of the staggered field spin-1/2 XXZ chain.

QI 3.12 Mon 18:15 BEY/0137

Scrambling the Information of Transmons using Interaction by Metamaterials — •Arne Schlabes and Mohammad Ansari — Forschungszentrum Jülich

Transmission lines made of capacitors in series and inductors to the ground form so called metamaterials with inverse dispersion relations. These Left-Handed materials allow for a multi-mode interaction of transmons coupled to the resonator. We use flux tunable qubits and parametric driving to excite resonator mode states. This occupation can be spread controllably from the resonator to a qubit and back to other resonator states. With this we realize a scrambling of information which started locally in one resonator state but is then encoded non-locally in multiple states. The precise composition of the final state depends on the parameters used to encode it, without them the initial state can not be recovered.