# TT 8: Focus Session: Quantum Interactive Dynamics I (joint session DY/TT)

Quantum many-body systems out of equilibrium represent a challenging frontier and have been shown to exhibit extremely rich phenomena. Recent experimental advances in building Noisy Intermediate-Scale Quantum (NISQ) devices have opened up a completely new territory in this context. The natural evolution implemented by NISQ devices is a quantum interactive dynamics generated by a combination of unitary gates and measurements. These platforms provide an opportunity to explore vastly larger parts of the Hilbert space and go beyond what can be realized in purely unitary systems. In pioneering works, an entanglement phase transition was identified in the dynamics of circuits of random unitary gates interleaved with local projective measurements. This phase transition separates a disentangling phase, obeying an area law, and an entangling phase obeying a volume law. Successively, it has been shown that additional phase transitions between different area phases can occur and new kinds of quantum phase transitions have been discovered. This session aims to give an overview of recent theoretical and experimental developments within this very active field and point towards the open questions.

Organized by Roderich Moesser (Dresden) and Frank Pollmann (München)

Time: Monday 9:30–12:45 Location: A 151

**Invited Talk** TT 8.1 Mon 9:30 A 151

**Quantum information phases in space-time: measurement-induced entanglement and teleportation on a noisy quantum processor** — •Vedika Khemani — Stanford University, USA

I will discuss the dynamics of monitored systems combining the ingredients of unitary evolution, measurements, and adaptive classical control. I will present various novel dynamical phases and phase transitions that arise in these systems, ranging from entanglement and teleportation phase transitions to "learnability" transitions in the ability to reconstruct quantum information from measurements. I will also discuss experimental realizations of these phenomena in noisy quantum processors.

**Invited Talk** TT 8.2 Mon 10:00 A 151

**Measurement phase transitions and universality** — •Adam Nahum — ENS Paris & CNRS

Repeated measurement can lead to a phase transition in quantum many-body dynamics. A subcritical rate of measurement allows complex, entangled states to evolve, while a supercritical measurement rate kills long-range entanglement. These phase transitions allow formal analogies with standard ordering transitions, but they are fundamentally different, partly as a result of the role played by quantum mechanical measurement randomness. Obtaining exact results for generic versions of the problem is challenging. I will sketch limits in which progress can be made (for example mean-field-like models, models in high dimensions, and noninteracting analogs).

**Invited Talk** TT 8.3 Mon 10:30 A 151

**Dual-unitary circuit dynamics** — •Pieter Claeys — Max Planck Institute for the Physics of Complex Systems, Nöthnitzer Str. 38, 01187 Dresden

Dual-unitary circuits are minimal models of many-body quantum dynamics characterized by an underlying space-time duality. This duality makes them amenable to exact analysis, while remaining chaotic, and in recent years dual-unitary circuits have been used to study e.g. aspects of operator dynamics, quantum chaos, operator scrambling, entanglement dynamics, and the interplay between unitary dynamics and projective measurements. In this work I will give an overview of recent developments in dual-unitary circuits, focusing on the connection with many-body dynamics.

TT 8.4 Mon 11:00 A 151

**Truncated Hilbert space approach for simulating dynamics in perturbed Ising chains** — •Nico Albert[1] and Hong-Hao Tu[2] — [1]Technische Universität Dresden, Dresden, Germany — [2]Ludwig-Maximilians-Universität München, Munich, Germany

Simulating dynamics in interacting quantum many-body systems is a challenging problem. We develop a truncated Hilbert space approach (THSA) and apply it to the quantum Ising chain with both transverse and longitudinal fields for studying its spectrum and quench dynamics. We find that the characteristic features of this model, such as $E_8$ particles with universal mass ratios, are well captured in the truncated Hilbert space approach. We also use this new method to study the confinement dynamics of domain-wall bound states in the ferromagnetic phase.

TT 8.5 Mon 11:15 A 151

**Entanglement Transitions in Unitary Circuit Games** — •Raúl Morral-Yepes[1,2], Adam Smith[3], Shivaji L. Sondhi[4], and Frank Pollmann[1,2] — [1]Technical University of Munich, Garching, Germany — [2]Munich Center for Quantum Science and Technology (MCQST), München, Germany — [3]University of Nottingham, Nottingham, UK — [4]University of Oxford, Oxford, UK

Repeated projective measurements in unitary circuits can lead to an entanglement phase transition as the measurement rate is tuned. In this work, we consider a different setting in which the projective measurements are replaced by dynamically chosen unitary gates that minimize the entanglement. This can be seen as a one-dimensional unitary circuit game in which two players get to place unitary gates on randomly assigned bonds at different rates: The "entangler" applies a random local unitary gate with the aim of generating extensive (volume law) entanglement. The "disentangler", based on limited knowledge about the state, chooses a unitary gate to reduce the entanglement entropy on the assigned bond with the goal of limiting to only finite (area law) entanglement. In order to elucidate the resulting entanglement dynamics, we consider three different scenarios: (i) a classical discrete height model, (ii) a Clifford circuit, and (iii) a general $U(4)$ unitary circuit. We find that both the classical and Clifford circuit models exhibit phase transitions as a function of the rate that the disentangler places a gate. In contrast, the entangler always wins when using Haar random unitary gates and we observe extensive, volume law entanglement for all non-zero rates of entangling.

TT 8.6 Mon 11:30 A 151

**Entanglement phases, localization and multifractality of monitored free fermions in two dimensions** — •Karim Chahine and Michael Buchhold — Institut für Theoretische Physik, Universität zu Köln, D-50937 Cologne, Germany

We investigate the entanglement structure and wave function characteristics of continuously monitored free fermions with $U(1)$-symmetry in 2D. By deriving the fermion replica-Keldysh field theory and a bosonic effective long-wavelength action, we explore the similarities and differences between entanglement phase transitions in 2D monitored fermions and Anderson-type localization transitions in 3D. Using exact numerical simulations, we establish the phenomenology of entanglement transitions in 2D monitored fermions, examining entanglement entropy, mutual information, and inverse participation ratio. At weak monitoring, we observe characteristic $L \log L$ entanglement growth and multifractal dimension $D_q = 2$, resembling a metallic Fermi liquid. At strong monitoring, exponentially localized wave functions lead to saturation, following an area law for entanglement. In between, the critical point exhibits entanglement scaling consistent with emergent conformal invariance and strong multifractality. Our numerical findings align well with mean-field analysis and a one-loop renormalization group treatment of the field theory, shaping the understanding of a monitoring-induced metal-to-insulator transition in entanglement content. This establishes 2D monitored fermions as a unique platform to explore the connection between non-unitary quantum dynamics in $D$ dimensions and quantum statistical mechanics in $D + 1$ dimensions.

TT 8.7 Mon 11:45 A 151

**Temporal Entanglement in Dual-Unitary Clifford Circuits with Probabilistic Measurements** — •Jiangtian Yao and Pieter Claeys — Max Planck Institute for the Physics of Complex Systems, Dresden, Germany

We study temporal entanglement in dual-unitary Clifford circuits with probabilistic measurements preserving spatial unitarity. We present exact results on characterizing the temporal entanglement barrier in the measurement-free regime. In the finite-measurement-rate regime, we numerically study the interplay between measurement rate and bath size. We connect the initial diffusive growth of temporal entanglement with bath size to a persistent random walk model and present an exact transfer-matrix approach for understanding how the system approaches the perfect-dephaser limit.

TT 8.8 Mon 12:00 A 151

**Universal correlations in mesoscopic many-body systems: Berry's Random Wave Model in Fock space** — •Florian Schöppl[1,2], Rémy Dubertrand[2], Juan Diego Urbina[2], and Klaus Richter[2] — [1]Northumbria University, NE1 8ST Newcastle upon Tyne, United Kingdom — [2]Institut für Theoretische Physik, Universität Regensburg, 93040 Regensburg, Germany

A complete characterization of quantum signatures of (mean-field) chaos in interacting many-body systems requires, besides the widely used universality of spectral correlations, the analysis of the corresponding universality for eigenstate correlations in Fock space.

We lift the concepts and techniques that characterize this universality in first-quantized systems, introduced by Berry [1] into the realm of interacting bosonic fields in [2]. The existence of a classical (mean-field) limit allows us to use of many-body semiclassical methods [3].

We employ them to investigate the universal statistical features of eigenstate correlations in Bose-Hubbard models.

[1] M. V. Berry, "Regular and irregular semiclassical wavefunctions", Journal of Physics A: Mathematical and General 10, 2083 (1977). [2] R. Dubertrand, F. Schöppl, J. D. Urbina, K. Richter, "Universal correlations in chaotic many-body quantum states: Fock space formulation of Berry*s random wave model", preprint (2023). [3] K.Richter, J.D. Urbina, S. Tomsovic. "Semiclassical roots of universality in many-body quantum chaos",J. Phys. A: Math. Theor. 55 453001 (2022)

TT 8.9 Mon 12:15 A 151

**Efficient Learning of Matrix Product States for Approximation of Purities in Quantum Many-Body Systems** — •Dmytro Kolisnyk, Raimel Medina, and Maksym Serbyn — Institute of Science and Technology Austria, Am Campus 1, 3400 Klosterneuburg, Austria

The defining feature of quantum many-body systems is an exponential scaling of the Hilbert space with the number of degrees of freedom. This exponential complexity naïvely renders the complete characterization of state, for instance via the complete set of bipartite Renyi entropies, a challenging task. Recently, the compact way of storing subregions' purities by encoding them as amplitudes of a fictitious quantum wave function, known as the entanglement feature (EF), was proposed. Matrix product state (MPS) encoding of such EF was obtained for Haar random states, however, the general applicability and practical usage of such encoding remained unclear. In this work, we demonstrate that EF can be efficiently learned using only polynomial amount of samples in the number of degrees of freedom through the so-called TTcross algorithm, assuming it is expressible as a finite bond dimension MPS. We benchmark this learning process on Haar and random MPS states, utilizing analytic insights. Additionally, we devise novel applications for the learned EF, such as quantifying the distance between different entanglement patterns and finding the optimal one-dimensional ordering of physical indices in a given state, highlighting the potential utility of proposed learning method in characterizing quantum many-body systems.

TT 8.10 Mon 12:30 A 151

**Quantum complexity phase transitions in monitored random circuits** — •Ryotaro Suzuki[1], Jonas Haferkamp[2], Jens Eisert[1], and Philippe Faist[1] — [1]Freie Universität Berlin — [2]Harvard University

Recently, the dynamics of quantum systems that involve both unitary evolution and quantum measurements have attracted attention due to the exotic phenomenon of measurement-induced phase transitions. At the same time, quantum complexity emerged as a key quantity for the identification of complex behaviour in quantum many-body dynamics. Quantum complexity of a quantum state is defined as the minimum number of unitary gates to generate the state by a quantum circuit. In this work, we investigate the dynamics of the quantum state complexity in monitored random circuits, where n qubits evolve according to a random unitary circuit and are individually measured with a fixed probability at each time step. We find that the growth behaviour of the exact quantum state complexity undergoes a phase transition when changing the measurement rate. Below a critical measurement rate, the complexity grows linearly in time until an exponential time in n. Above, the complexity does not grow more than polynomially in n. We lower bound the exact state complexity in the former regime using recently developed techniques based on algebraic geometry.