The Abdus Salam International Centre for Theoretical Physics

Workshop on Dynamics of Monitored Quantum Many-Body Systems | (SMR 3868)

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ICTP, Trieste, Italy

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Measurement phase transitions in the no-click limit as quantum phase transitions of a non-hermitean vacuum

T01

Abstract preparation for a Workshop

Guido Giachetti[1], Andrea de Luca[1]

[1] *CYU Cergy Paris University*

We study an exactly solvable model of monitored dynamics in a spin-1/2 Brownian Heisenberg model, where each spin is constantly perturbed by weak measurements. We make use of the replica trick to account for the Born's rule weighting of the measurement outcomes in the study of purification and other observables. We find that the nature of the phase transition strongly depends on the number of replicas used in the calculation, with the appearance of non-perturbative logarithmic corrections that destroy the purifying phase. Specifically, we observe that the purification time of a mixed state in the weak measurement phase is always exponentially long in the system size for arbitrary strong measurement rate.

T02

Title- Many-body quantum chaos with randomized measurements

Authors- Theory: L. Joshi, A. Elben, A. Vikram, B. Vermersch, V. Galitski, P. Zoller
Experiment: K. Collins, A. De, W. Morong, C. R. Monroe

Abstract- The spectral form factor (SFF), characterizing statistics of energy eigenvalues, is a key diagnostic of many-body quantum chaos. In addition, partial spectral form factors (pSFFs) can be defined which refer to subsystems of the many-body system. They provide unique insights into energy eigenstate statistics of many-body systems. We propose a protocol that allows the measurement of the SFF and pSFFs in quantum many-body spin models, within the framework of randomized measurements. Our protocol provides a unified testbed to probe many-body quantum chaotic behavior, thermalization and many-body localization in closed quantum systems. Furthermore, we present implementation of this protocol on a trapped ion quantum simulator employing the use of local random rotations and measurements.

T03

Phase transition in random circuit sampling

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The promise of quantum computers is to efficiently realize entangled quantum states for which classical simulation requires exponential resources [1]. In practice quantum computers are subject to noise which limits the growth of entanglement and in this way limits the effective Hilbert space that can be used for quantum computation. Using the example of a random circuit we analyze the competition between the entangling effect of the circuit and hardware noise. This competition manifests in a first order quantum phase transition controlled by the error per unit time in the circuit, i.e. a noise induced phase transition. We demonstrate theoretically and numerically that the transition manifests as a discontinuity and the associated finite size critical behavior in the cross-entropy benchmark [2] and in this way can be observed experimentally. We leverage this theory to identify the noise induced phase transition experimentally [2]. Identification of the phase transition allows us to assess the useful effective Hilbert space of a quantum computer for the purpose of Random Circuit Sampling task and estimate costs of classical simulations.

[1] Frank Arute, Nature **574**, 505 (2019).
[2] A. Morvan, *et. al.*, arXiv:2304.11119 (2023).

T04

Verifiable learning of post-measurement quantum state ensembles without postselection

Max McGinley

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Recently, a great deal of interest has emerged in studying statistical ensembles of quantum states that arise from dynamics that involve measurement, including measurement-induced entanglement phase transitions and the projected ensemble. However, most current methods to experimentally probe such phenomena run into the challenge of postselection—namely, one must run the experiment sufficiently many times such that all possible measurement outcomes each occur multiple times, which requires an exponential-in-system-size number of repetitions.

In this talk, I will present a method to infer arbitrary properties of post-measurement ensembles that does not suffer from this issue, which leverages the formalism of classical shadow tomography. By combining experimental data with idealised classical simulations of the device, many properties of the ensemble can be learned using a feasible number of experimental repetitions. Crucially, I will show that even when the classical simulation is imperfect, and/or the device is noisy, once can use the experimental data to construct tight, rigorous, two-sided bounds on the observable of interest, which give guarantees that its true value for the *quantum* device lies within some narrow window. This allows one to obtain verifiable constraints on measurement-averaged entanglement, as well as measures of randomness such as the frame potential. I will conclude by discussing the resource requirements of this method, both in terms of sample complexity and classical computational cost.

T05

Theory of free fermions under random projective measurements

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We develop an analytical approach to the study of one-dimensional free fermions subject to random projective measurements of local site occupation number, based on the Keldysh path-integral formalism and replica trick. In the limit of rare measurements, $\gamma/J \ll 1$ (where γ is measurement rate per cite and J is hopping constant in the tight-binding model), we derive a non-linear sigma model (NLSM) as an effective field theory of the problem. Its replica-symmetric sector is described by a $U(2)/U(1) \times U(1) \simeq S_2$ sigma model with diffusive behavior, and the replica-asymmetric sector is a two-dimensional NLSM defined on $SU(R)$ manifold with the replica limit $R \to 1$. On the Gaussian level, valid in the limit $\gamma/J \to 0$, this model predicts a logarithmic behavior for the second cumulant of number of particles in a subsystem and for the entanglement entropy. However, the one-loop renormalization group analysis allows us to demonstrate that this logarithmic growth saturates at a finite value $\sim (J/\gamma)^2$ even for rare measurements, which corresponds to the area-law phase. This implies the absence of a measurement-induced entanglement phase transition for free fermions. The crossover between logarithmic growth and saturation, however, happens at exponentially large scale, $\ln l_{\rm corr} \sim J/\gamma$. This makes this crossover very sharp as a function of the measurement frequency γ/J, which can be easily confused with a transition from the logarithmic to area law in finite-size numerical calculations. We have performed a careful numerical analysis, which supports our analytical predictions .

T06

Eran Sela (Tel Aviv University)

Title: Identifying dissipative phase transitions from entropy measurements

Abstract: Dissipative phase transitions (DPTs) occur when a small quantum system interacts with a bath of harmonic oscillators. They are expected to be accompanied by an entropy change, signaling the decoherence of the system. I will review recent experimental progress showing that charge sensors of quantum dot systems allow measurement of entropy through Maxwell relations, as well as theoretical predictions on exotic states that can be detected using this method. Typically, a weak coupling to the charge sensor is assumed. Here I will argue theoretically that more generally these experiments realize DPTs due to the decoherence of the system by the charge sensor. This may allow for a first observation of the equilibrium Kosterlitz-Thouless transition in the spin-boson model in a mesoscopic system.

T07

Orthogonality catastrophe beyond bosonization from post-selection of measurements

Martino Stefanini, Jamir Marino

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In this work [1], we consider a one-dimensional fermionic system subjected to a local, post-selected continuous weak measurement of the density. The effective dynamics of this system realizes a non-Hermitian version of the well-known problem of a local scatterer in a fermionic system and its ensuing orthogonality catastrophe [2]. The latter is a paradigmatic problem in solid state physics, whose solution can be elegantly obtained through bosonization [3]. Notwithstanding the apparent simplicity of the non-Hermitian scenario, we show numerically that its dynamics is richer than its Hermitian counterpart. We discover that the time evolution of various observables, such as the return amplitude and the absorbed energy, can be smoothly tuned from a regime in which bosonization works to a regime in which it fails, the tuning parameter being simply the fermion density. We put forward an interpretation of the observed behaviors in terms of the existence of special momentum modes which are strongly scattered by the non-Hermitian impurity, but lie far from the Fermi surface. The model considered in this work provides a conceptually simple and non-perturbative route for the observation of effects beyond bosonization.

[1] Martino Stefanini, Jamir Marino, in preparation (2023).
[2] P. W. Anderson, Phys. Rev. Lett. **18**, 1049 (1967).
[3] K. D. Schotte and U. Schotte, Phys. Rev. **182**, 479 (1969).

T08

Disordered monitored free fermions

Marcin Szyniszewski [1] **, Oliver Lunt** [2,3,1] **, and Arijeet Pal** [1]

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Scrambling of quantum information in unitary evolution can be hindered due to measurements and localization. Both these effects lead to pinning of the quantum mechanical wavefunction resulting in suppression of entanglement in the steady state. In monitored free-fermionic models the steady state undergoes an entanglement transition from a critical logarithmically to area-law entangled steady state due to the coupling to an environment [1]. However, in an isolated system arbitrarily weak disorder in one dimension leads to Anderson localization. We investigate a free-fermion system in a random field subject to continuous monitoring, which enables us to probe the non-trivial interplay between measurement-induced phases and disorder. Through the careful analysis of the effective central charge, entanglement entropy, and density-density correlations, we show that the critical phase with conformal symmetry is stable under disorder perturbations until a finite critical disorder strength. We find that the universality class of the transition at finite disorder and dissipative coupling is consistent with the Berezinskii-Kosterlitz-Thouless across the extended phase diagram. Furthermore, destructive interference responsible for Anderson localization is destroyed under finite monitoring strength and the steady state orbital wavefunction exhibits a power-law decay. Our results indicate that the critical phase is robust to disorder and the area-law phase is distinct from Anderson localization at weak dissipation. Our work opens the avenue to probe this interesting phase transition in experiments involving electrons in quantum dot arrays and nanowires, as well as allow quantum control of entangled states of electrons.

[1] O. Alberton, M. Buchhold, and S. Diehl, Phys. Rev. Lett. **126**, 170602 (2021).

T09

Measurement-induced phase transitions in disordered quantum many-body dynamics under continuous monitoring

Kazuki Yamamoto [1,2] **and Ryusuke Hamazaki** [3]

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Localization, which is typically induced by disorder, is an exotic phenomenon where a quantum state fails to spread over the entire Hilbert space. Recently, measurement is utilized as another mechanism to localize a quantum state in nonunitary quantum circuits and continuously monitored systems, which exhibit novel quantum phenomena dubbed measurement-induced phase transitions (MIPTs). However, while both the disorder and the measurement localize the wave function and suppress the entanglement spreading, it is still not clear whether they exhibit the same localization properties.

In this talk, we study the localization properties of continuously monitored dynamics and associated MIPTs in disordered quantum many-body systems on the basis of the quantum trajectory approach [1]. By calculating the fidelity between random quantum trajectories, we demonstrate that the disorder and the measurement can lead to dynamical properties distinct from each other, although both have a power to suppress the entanglement spreading. In particular, in the large-disorder regime with weak measurement, we elucidate that the fidelity exhibits an anomalous power-law decay before saturating to the steady-state value. Furthermore, we propose a general method to access physical quantities for quantum trajectories in continuously monitored dynamics without resorting to postselection. It is argued that this scheme drastically reduces the cost of experiments. Our results can be tested in ultracold atoms subject to continuous measurement.

[1] K. Yamamoto and R. Hamazaki, Phys. Rev. B **107**, L220201 (2023).

T10

Abstract preparation for a Workshop

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We study dynamical phase transitions occurring in the stationary state of the dynamics of integrable many-body non-hermitian Hamiltonians, which can be either realized as a no-click limit of a stochastic Schrödinger equation or using spacetime duality of quantum circuits. In two specific models, the Transverse Field Ising Chain and the Long Range Kitaev Chain, we observe that the entanglement phase transitions occurring in the stationary state have the same nature as that occurring in the vacuum of the non-hermitian Hamiltonian: bounded entanglement entropy when the imaginary part of the quasi-particle spectrum is gapped and a logarithmic growth for gapless imaginary spectrum. This observation suggests the possibility to generalize the area-law theorem to non-Hermitian Hamiltonians.

[1] C. Zerba, A. Silva, arXiv:2301.07383