International Workshop

Many-body systems out of equilibrium: recent advances and future directions

19. —23. September 2022, Slovenia

Invited Speakers:

Yevgeny Bar Lev
(Ben-Gurion University, Israel)
Berislav Buča
(University of Oxford, UK)
Marcello Dalmonte
(ICTP Trieste, Italy)
Wojciech De Roeck
(KU Leuven, Belgium)
Anatoly Dymarsky
(University of Kentucky, US)
John Goold
(Trinity College Dublin, Ireland)
Christian Gross
(University of Tübingen, Germany)
Markus Heyl
(University of Augsburg, Germany)
Marcin Mierzejewski
(Wrocław University of Science and Technology, Poland)
Oren Raz
(Weizmann Institute, Israel)
Jonas Richter
(University College London, UK)
Marcos Rigol
(Penn State, US)
Martin Ringbauer
(University of Innsbruck, Austria)
Achim Rosch
(University of Cologne, Germany)
Marco Schiro
(Collège de France)
Markus Schmitt
(University of Cologne, Germany)
Dries Sels
(Flatiron Institute, US)
Philipp Strasberg
(Universitat Autònoma de Barcelona, Spain)

Scientific Organizers:

Zala Lenarčič
(Jožef Stefan Institute, Slovenia)
Lev Vidmar
(Jožef Stefan Institute and University of Ljubljana, Slovenia)
Jürgen Schnack
(University of Bielefeld, Germany)
Robin Steinigeweg
(University of Osnabrück, Germany)

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University of Oldenburg
University of Osnabrück

Monday (19.09.)	Tuesday (20.09.)	Wednesday (21.09.)	Thursday (22.09.)	Friday (23.09.)
	Gold (9:00-9:45) Dalmonte (9:45-10:30)	Rosch (9:00-9:45) Heyl (9:45-10:30)	Sels (9:00-9:45) Mierzejewski (9:45-10:30)	Raz (9:00-9:45) Wang (9:45-10:10)
Transport from Ljubljana City (9:30) Ljubljana Airport (10:30)	Coffee (10:30-11:00)	Coffee (10:30-11:00)	Coffee (10:30-11:00)	Coffee / Early Departure (10:10-10:40)
	Schmitt (11:00-11:45) Nandy (11:45-12:10) Schnack (12:10-12:35)	Schiro (11:00-11:45) Herbrych (11:45-12:10) Bonča (12:10-12:35)	Bar Lev (11:00-11:45) Šuntajs (11:45-12:10) Hopjan (12:10-12:35)	Heitmann (10:40-11:05 Prelovšek (11:05-11:50)
Lunch (12:30-14:00)	Lunch (12:35-14:00)	Lunch (12:35-14:00)	Lunch (12:35-14:00)	Lunch (12:20-14:00)
Rigol (14:00-14:45) Dymasrsky (14:45-15:30)	Strasberg (14:00-14:45) Buča (14:45-15:30)	Free Afternoon	De Roeck (14:00-14:45) Richter (14:45-15:30)	Transport to Ljubljana City / Airport
Coffee (15:30-16:00)	Coffee (15:30-16:00)		Coffee (15:30-16:00)	
Ringbauer (16:00-16:45)	Gross (16:00-16:45)		Posters (16:00-17:30)	
Łydżba (16:45-17:10) Reimann (17:10-17:35)	Discussions (16:45-18:30)		Discussions (17:30-18:30)	
Dinner (18:30-20:00)	Dinner (18:30-20:00)	Dinner (18:30-20:00)	Dinner (18:30-20:00)	

TALKS

Investigating quantum annealing strategies to solve the Fermi-Hubbard model

Kunal Vyas [1,2], Fengping Jin [1], Kristel Michielsen [1,2,4], Hans de Raedt [1,3]

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[4] JARA-CSD, Jülich-Aachen Research Alliance, 52425 Jülich, Germany.

Quantum annealing can help in finding the ground state of Hamiltonians describing many body systems. One such Hamiltonian is the Fermi-Hubbard Hamiltonian. We have tried different annealing strategies to see what kind of driving Hamiltonian can be used to calculate the ground state of the Hubbard model. We present some of the strategies considered and the corresponding results. We also outline our plan to study quantum annealing for a system described by the Hubbard Hamiltonian and coupled to a bath to investigate the effect of the environmental temperature and disorder on the ideal quantum annealing process for finding the ground state.

[1] H. De Raedt and K. Michielsen, Handbook of Theoretical and Computational Nanotechnology, Vol. 3: Quantum and molecular computing, quantum simulations, Chapter 1, pp. 248, M. Rieth and W. Schommers eds., American Scientific Publisher, Los Angeles (2006)

Iterative construction of most necessary conserved quantities

Iris Ulčakar [1], Zala Lenarčič [1]

[1] *Jožef Stefan Institute, Department for Theoretical Physics, Ljubljana, Slovenia*

General Gibbs ensembles (GGEs) have been proposed as a local steady state description of integrable many-body systems after a quantum quench. Similarly, GGEs also approximately describe the non-equilibrium steady states of integrable systems weakly coupled to non-equilibrium Markovian baths [1, 2, 3]. We present an iterative method for the latter case, constructing the most necessary conserved quantities for an efficient truncated GGE description. Guided by the integrability-breaking perturbations, the space of conserved quantities is spanned by the action of the baths' super-operators.

[1] F. Lange, Z. Lenarčič, and A. Rosch, Phys. Rev. B **97**, 165138 (2018).

[2] F. Lange, Z. Lenarčič, and A. Rosch, Phys. Rev. B **97**, 024302 (2018).

[3] F. Lange, Z. Lenarčič, and A. Rosch, Nat. Comm. **8**, 15767 (2017).

Rigol: Typical eigenstate entanglement entropy as a diagnostic of quantum chaos and integrability

Marcos Rigol

Department of Physics, The Pennsylvania State University, University Park, Pennsylvania 16802, USA

The typical entanglement entropy of subsystems of random pure states is known to be (nearly) maximal, while the typical entanglement entropy of random Gaussian pure states has been recently shown to exhibit a qualitatively different behavior, with a coefficient of the volume law that depends on the fraction of the system that is traced out [1]. We discuss evidence that the typical entanglement entropy of eigenstates of quantum-chaotic Hamiltonians mirrors the behavior in random pure states [2], while that of integrable Hamiltonians mirrors the behavior in random Gaussian pure states [3]. Based on these results, we conjecture that the typical entanglement entropy of Hamiltonian eigenstates can be used as a diagnostic of quantum chaos and integrability [3]. We discuss subtleties that emerge as a result of conservation laws, such as particle number conservation [1,2], as well as of lattice translational invariance [4].

[1] E. Bianchi, L. Hackl, M. Kieburg, MR, and L. Vidmar, PRX Quantum **3**, 030201 (2022).

[2] L. Vidmar and MR, PRL 119 220603 (2017).

[3] T. LeBlond, K. Mallayya, L. Vidmar, and MR, PRE 100 062134 (2019).

[4] L. Vidmar, L. Hackl, E. Bianchi, and MR, PRL 119 020601 (2017).

Dymarsky: Generalized Eigenstate Thermalization Hypothesis in 2d CFTs

Anatoly Dymarsky

Department of Physics & Astronomy, University of Kentucky

I will discuss the Eigenstate Thermalization Hypothesis in conformal field theories, with the emphasis on 2d case. In this case infinite-dimensional Virasoro symmetry gives rise to integrable quantum KdV structure in the stress-energy sector. Taking this structure into account leads to Generalized ETH (GETH) formulation that matches an individual eigenstate to the KdV GGE ensemble.

Brownian single-file transport of hard rods with adhesive interactions

Sören Schweers [1], Alexander P. Antonov [1], Artem Ryabov [2], Philipp Maass [1]

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Single-file Brownian transport processes are important for various applications in nature and technology. To study these processes, the Brownian asymmetric simple exclusion process (BASEP) was introduced as a standard reference model [1-3]. Here we discuss the effect of additional adhesive interparticle interactions, which occur in a wide range of systems, from interactions between simple spherical colloidal particles up to hydrogen-bonding, p- p stacking and covalent-like bonding between molecules with complex structure in biology. To explore the impact of adhesive interactions on single-file motion, we use Baxter's sticky core model [4] and develop a new method to tackle the singularity in this potential in Brownian dynamics simulations. Our new method is validated by comparing simulated equilibrium density profiles with profiles calculated by minimizing the exact density functional for the sticky core model [5]. We also present first simulation results for the impact of the adhesive interaction on the nonequilibrium dynamics in driven single-file transport through periodic potentials.

[1] D. Lips, A. Ryabov, and P. Maass, Phys. Rev. Lett. **121**, 160601 (2018).

[2] D. Lips, A. Ryabov, and P. Maass, Phys. Rev. E **100**, 052121 (2019).

[3] A. Ryabov, D. Lips, and P. Maass, J. Phys. Chem. C **123**, 5714 (2019).

[4] R. J. Baxter, J. Chem. Phys. **49**, 2770 (1968).

[5] J. K. Percus, J. Stat. Phys. **28**, 67 (1982).

Dual unitary circuits in random geometries

Yusuf Kasim

Ljubljana University

Recently introduced dual unitary brickwork circuits have been recognised as paradigmatic exactly solvable quantum chaotic many-body systems with tunable degree of ergodicity and mixing. Here we show that regularity of the circuit lattice is not crucial for exact solvability. We consider a circuit where random 2-qubit dual unitary gates sit at intersections of random arrangements of straight lines in two dimensions (mikado) and analytically compute the variance of the spatio-temporal correlation function of local operators. Note that the average correlator vanishes due to local Haar randomness of the gates. The result can be physically motivated for two random mikado settings. The first corresponds to the thermal state of free particles carrying internal qubit degrees of freedom which experience interaction at kinematic crossings, while the second represents rotationally symmetric (random euclidean) space-time.

Ringbauer: Quantum Computing and Simulation with Trapped Ions

Martin Ringbauer

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Cold trapped ions are one of the most powerful platforms for quantum information processing [1]. In this talk, I will cover the basic principles of ion traps, introduce the tools we use for manipulating quantum information in trapped ions, and map out the large playground that this system presents. A few key experiments that have been achieved in this platform include topological quantum error correction [2,3] and digital quantum simulation of lattice gauge models [4]. Lately, the platform has been extended to enable universal control over multi-level Hilbert spaces [5], which opens up a wealth or new opportunities. I will conclude with an outlook towards the next steps for this platform.

[1] P. Schindler, et al., New J. Phys. 15, 123012 (2013)
[2] D. Nigg, et al., Science 345, 302-305 (2014)
[3] L. Postler, et al., Nature 605, 675-780 (2022)
[4] E.A. Martinez, et al., Nature 534, 516-519 (2016)
[5] M. Ringbauer, et al., Nature Physics (2022)

Łydżba: Generalized thermalization in quantum-chaotic quadratic Hamiltonians

Patrycja Łydżba [1], Marcin Mierzejewski [1], Marcos Rigol [2], Lev Vidmar [3,4]

[1] Wrocław University of Science and Technology, Department of Theoretical Physics, Wrocław, Poland
[2] The Pennsylvania State University, Department of Physics, Pennsylvania, USA
[3] J. Stefan Institute, Department of Theoretical Physics, Ljubljana, Slovenia
[4] University of Ljubljana, Department of Physics, Ljubljana, Slovenia

The concept of generalized thermalization has proved to be successful in many theoretical works and experiments. Nevertheless, there are still unresolved puzzles that concern quadratic Hamiltonians. For example, some physically relevant observables, like site or quasimomentum mode occupations, do not always equilibrate. This failure prevents a meaningful comparison of the long-time expectation values of observables with the predictions of the generalized Gibbs ensemble (GGE).

A new perspective in these studies has been recently provided by the class of quantum-chaotic quadratic (QCQ) Hamiltonians, which properties are consistent with single-particle quantum chaos [1,2]. Paradigmatic local examples include the three-dimensional Anderson model in the delocalized phase [1-3] and chaotic tight binding billiards [4]. Non-local counterparts include the power-law random banded matrix model in the delocalized phase [5] and the quadratic Sachdev-Ye-Kitaev model [1,2]. As single-particle quantum chaos is manifested in their spectral properties, entanglement entropies of typical many-body eigenstates and matrix elements of observables in a single-particle sector, a natural question arises whether QCQ Hamiltonians should be considered as integrable or not.

In this talk, we argue that equilibration is ensured in QCQ models by the single-particle eigenstate thermalization hypothesis (ETH). Simultaneously, the GGE is generally different from the grand canonical ensemble, and it is needed to describe the long-time expectation values of observables. An interesting observation is that Lagrange multipliers of the GGE are smooth functions of single-particle energies in QCQ Hamiltonians. Again, we connect this property with the single-particle ETH.

[1] Phys. Rev. B 103, 104206 (2021).
[2] Phys. Rev. B 104, 214203 (2021).
[3] Annals of Physics, 168469 (2021).
[4] ArXiv:2206.07078 (2022).
[5] Phys. Rev. Lett. 125, 180604 (2020).

Many-body systems out of equilibrium: recent advances and future directions

On the hardness of quadratic unconstrained binary optimization problems

V. Mehta [1,3], F. Jin [1], K. Michielsen [1,2,3], H. De Raedt [1,4]

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[2] JARA-CSD, Jülich-Aachen Research Alliance, 52425 Jülich, Germany
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We use exact enumeration to characterize the solutions of quadratic unconstrained binary optimization problems of less than 21 variables in terms of their distributions of Hamming distances to close-by solutions. We also perform experiments with the D-Wave Advantage 5.1 quantum annealer, solving many instances of up to 170-variable, quadratic unconstrained binary optimization problems. Our results demonstrate that the exponents characterizing the success probability of a D-Wave annealer to solve a QUBO correlate very well with the predictions based on the Hamming distance distributions computed for small problem instances.

[1] Front. Phys. 10:956882 (2022).

Anomalous Diffusion and Prethermalization in an Interacting Flat Band System

Mirko Daumann [1], Thomas Dahm [1]

[1] *University of Bielefeld, Faculty of Physics, Bielefeld, Germany*

We study the broadening of initially localized wave packets in a quasi one-dimensional diamond ladder with interacting, spinless fermions. The lattice possesses a flat band causing localization. We place special focus on the transition away from the flat band many-body localized case by adding very weak dispersion. By doing so, we allow propagation of the wave packet on significantly different time scales which causes anomalous diffusion. Due to the temporal separation of dynamic processes, an interaction-induced, prethermal equilibrium becomes apparent. This behavior is akin to systems with two, light and heavy, particle species, which have been discussed as possibility to realize disorder-free many-body localization. The results are discussed in the context of the Born-Oppenheimer approximation for interpretation.

Many-body systems out of equilibrium: recent advances and future directions

Reimann: Provable Thermalization

Peter Reimann

University of Bielefeld, Faculty of Physics, Bielefeld, Germany

The universal and irreversible tendency of nonequilibrium states towards thermal equilibrium is an everyday experience in the macroscopic world, but, in spite of more than a century of theoretical efforts, it has still not been satisfactorily reconciled with the basic laws of physics, which govern the microscopic world and which are fundamentally reversible. Much effort has been devoted to identify and understand exceptions from this standard scenario, while rigorous statements regarding the occurrence of thermalization are still rather scarce. Here, some recent and not so recent such statements are highlighted.

Goold: Quantum Joule Paddle Bucket, thermometry and transport

John Goold et al

School of Physics, Faculty of Engineering, Mathematics & Science,Trinity College, Dublin, Ireland

Joule's paddle bucket experiment was one of the defining experiments of 19th century physics demonstrating the mechanical equivalent of heat. In the first part of the talk we use the original concept by Joule as an inspiration for a novel quantum thermometry scheme based on the eigenstate thermalization hypothesis [1]. Using only a few basic assumptions about chaotic quantum systems — namely, the eigenstate thermalisation hypothesis and the equations of diffusive hydrodynamics — we show that the qubit undergoes pure exponential decoherence at a rate that depends on the temperature of its surroundings. We verify our predictions by numerical experiments on a quantum spin chain that thermalises after absorbing energy from a periodic drive. In the second part of the talk I will give an overview of recent work that we are peforming on the propagation of spin helix states in the XXZ spin chain [2]. We use kernel polynomial methods to extract the frequency representation of the correlation function in the diagonal ensemble and show that the correct transport exponents can be recovered in contrast to recent ultra-cold experiments that extract temporal decay exponent of the contrast.

[1] M.T. Mitchsion, A. Purkayasta, Phys. Rev. A 105, L030201 (2022)

[2] C. Chiracane, M. T. Mitchison, S. Pappalardi S. R. Clark and J. Goold in progress (2022)

Solitons in overdamped Brownian motion through periodic potentials

Alexander P. Antonov [1], Artem Ryabov [2], and Philipp Maass [1]

[1] *Osnabrück University, Department of Physics, Osnabrück, Germany*
[2] *Charles University, Faculty of Mathematics and Physics, Department of Macromolecular Physics, Prague, Czech Republic*

Solitons are commonly known in systems with inertia as waves that propagate without dispersion due to nonlinear effects, like in the classical Frenkel-Kontorova model. We show that solitons can occur in the absence of inertia for fully overdamped Brownian dynamics of hard spheres in periodic potentials at high particle densities [1]. This Brownian asymmetric simple exclusion process (BASEP) shows many intriguing particle size effects in nonequilibrium dynamics [2-6]. The solitons manifest themselves as periodic sequences of different assemblies of particles moving in the limit of zero noise, where transport of single particles is not possible. Even at low temperature, they give rise to particle currents that appear in band-like structures around certain particle diameters. In effectively frustrated systems, where mutual blocking effects are expected to prevent particle motion, solitons can be generated as rare events and lead to noticeable particle currents [7]. These currents follow a scaling behavior, where for small systems the current is proportional to the soliton generation rate, and for large systems given by the geometric mean of the generation rate and velocity. All the predicted features should occur in a broad class of periodic systems and are amenable to experimental tests.

[1] A.P. Antonov, A. Ryabov and P. Maass, to appear in Phys. Rev. Lett. (2022); https://arxiv.org/abs/2204.14181.
[2] D. Lips, A. Ryabov, and P. Maass, Phys. Rev. Lett. **121**, 160601 (2018).
[3] D. Lips, A. Ryabov, and P. Maass, Phys. Rev. E **100**, 052121 (2019).
[4] A. Ryabov, D. Lips, and P. Maass, J. Phys. Chem. C **123** 5714 (2019)
[5] E. Cereceda-López, D. Lips, A. Ortiz-Ambriz, A. Ryabov, P. Maass, and P. Tierno, Phys. Rev. Lett. **127**, 214501 (2021).
[6] A.P. Antonov, A. Ryabov and P. Maass, J. Chem. Phys. **155** 184102 (2021)
[7] A.P. Antonov, D. Voráč, A. Ryabov and P. Maass, https://arxiv.org/abs/2203.06372.

POSTERS

Dalmonte: Data mining the many-body problem - from universal behaviour to Kolmogorov complexity

Marcello Dalmonte

ICTP and SISSA, Trieste, Italy

Many-body systems are typically characterised via low-order correlation functions, that are directly related to response functions. In this talk, I will show how it is possible to provide a characterisation of many-body systems via a direct and assumption-free data mining of one of the pillars of both classical and quantum statistical mechanics - the partition function. The core idea of this programme is the fact that, once sampled stochastically (such as in experiments with in-situ imaging, or via Monte Carlo simulations), partitions functions can be construed as a very high-dimensional manifolds. Such manifolds can be characterised via basic topological concepts, in particular, by their intrinsic dimension.

I will discuss theoretical results for both classical and quantum many-body spin systems that illustrate how data structures undergo structural transitions whenever the underlying physical system does, and display universal (critical) behavior in both classical and quantum mechanical cases. I will conclude with remarks on the applicability of our theoretical framework to synthetic quantum systems (quantum simulators and quantum computers), and emphasize its potential to provide a direct, scalable measure of Kolmogorov complexity of output states.

Based on: Phys. Rev. X **11**, 011040, Phys. Rev. X Quantum **2**, 030332 (2021), unpublished

Schmitt: Simulating non-equilibrium quantum matter with neural quantum states

Markus Schmitt

University of Cologne, Germany

The classical simulation of many-body quantum dynamics constitutes a pivotal challenge due to the typical growth of entanglement in the course of the evolution. I will discuss how combining the time-dependent variational principle with neural quantum states allows us to overcome some of the current limitations. As an application I will address quantum phase transition dynamics in two spatial dimensions of a model that is experimentally realized in Rydberg quantum simulators.

Many-body systems out of equilibrium: recent advances and future directions

Prelovšek: Slow diffusion in modulated spin chains: periodic vs. random systems

Peter Prelovšek [1], Jacek Herbrych [2], Marcin Mierzejewski [2]

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[2] *Wroclaw University of Scinece and Technology, Wroclaw, Poland*

It is general observation that one-dimensional spin chains, and equivalently interacting fermionic chains, reveal a transition/crossover to many-body localization (MBL) when subjected to large random or quasiperiodic (QP) potentials, which is manifested in strong dependence of the d.c. transport quantities on potential strength W. The qualitative difference is that in random systems numerical results show large sample-sample fluctuations [1], while QP systems can/do not. We present results for the high-temperature spin conductivity σ in QP chains, which reveal an exponential-like dependence on W over several decades, without any clear indication of a well-defined transition to MBL. Moreover, replacing the QP potential with a simpler periodic one, the variation remains qualitatively similar up to large values of W.

[1] J. Herbrych, M. Mierzejewski, and P. Prelovšek, Phys. Rev. B **105**, L081105 (2022).

Heitmann: Exact diagonalization of large isotropic quantum spin rings

Tjark Heitmann [1], Jürgen Schnack [2], Robin Steinigeweg [1]

[1] *University of Osnabrück, Department of Physics, Osnabrück, Germany*

[2] *University of Bielefeld, Faculty of Physics, Bielefeld, Germany*

Numerical studies of quantum spin systems are notoriously limited by the exponential growth of the underlying Hilbert-space dimension with system size N. To alleviate this, one often resorts to the use of symmetries like, e.g., the conservation of total magnetization and additional lattice symmetries in order to push the limit of computationally available system sizes. For isotropic exchange interactions, the spin-rotational symmetry SU(2) can be used, where the Hamiltonian matrix is block-structured according to the total spin- and magnetization quantum numbers [1]. For periodic systems, the relevant dimension of the matrix blocks can be further reduced using the translational symmetry [2]. While mathematically straightforward, the combined use of the spin-rotational SU(2) symmetry with additional real-space symmetries is quite challenging in practice. Here we demonstrate how the computational effort of the symmetry adaptation procedure can be minimized in order to achieve the complete exact diagonalization of up to N=27 spin-1/2 spins.

[1] R. Schnalle, J. Schnack, *Calculating the energy spectra of magnetic molecules: application of real- and spin-space symmetries,* Int. Rev. Phys. Chem. **29** (2010) 403-452
[2] T. Heitmann, J. Schnack, *Combined use of translational and spin-rotational invariance for spin systems,* Phys. Rev. B **99** (2019) 134405

Many-body systems out of equilibrium: recent advances and future directions

Nandy: Autoencoder-assisted learning of Hamiltonians

Sourav Nandy and Zala Lenarčič

Jožef Stefan Institute, Department for Theoretical Physics, Ljubljana, Slovenia

Reconstructing (effective) Hamiltonians from local measurements has several appealing applications. In the realm of quantum simulators, it can serve certification purposes. In condensed matter, it can reveal the effective minimal models. Out-of-equilibrium, such as in Floquet driven setups, it can reconstruct the effective stroboscopic evolution. Here we propose an algorithm for Hamiltonian reconstruction, assisted by machine learning pre-processing of data, with data set containing (quasi-)thermal measurements of local operators. Efficient and precise reconstruction of local Hamiltonians is possible, while long-range interacting Hamiltonians are reconstructed approximately. We use the algorithm to show that in closed Floquet driven setups, the system is on the prethermal plateau and throughout the heating regime locally described by a thermal state with effective Hamiltonian becoming less and less local as the system heats up.

Schnack: Observation of phase synchronization and alignment during free induction decay of quantum spins with Heisenberg interactions

Jürgen Schnack[1], Heinz-Jürgen Schmidt[2], Christian Schröder[3], Patrick Vorndamme[1]

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[2] Osnabrück University, Dept. of Physics, Osnabrück, Germany
[3] University of Applied Sciences, Bielefeld, Germany

Equilibration of observables in closed quantum systems that are described by a unitary time evolution is a meanwhile well-established phenomenon apart from a few equally well-established exceptions. Here we report the surprising theoretical observation that integrable as well as non-integrable spin rings with nearest-neighbor or long-range isotropic Heisenberg interaction not only equilibrate but moreover also synchronize the directions of the expectation values of the individual spins. We highlight that this differs from spontaneous synchronization in quantum dissipative systems. In our numerical simulations, we investigate the free induction decay (FID) of an ensemble of up to N = 25 quantum spins with s = 1/2 each by solving the time-dependent Schrödinger equation numerically exactly. Our findings are related to, but not fully explained by conservation laws of the system. The phenomenon very robust against for instance random fluctuations of the Heisenberg couplings. Synchronization is not observed with strong enough symmetry-breaking interactions such as the dipolar interaction and is also not observed in closed-system classical spin dynamics.

[1] P. Vorndamme, H.-J. Schmidt, Chr. Schröder, J. Schnack, New J. Phys. 23 (2021) 083038

Many-body systems out of equilibrium: recent advances and future directions

Wang: Eigenstate Thermalization Hypothesis and Its Deviations from Random-Matrix Theory beyond the Thermalization Time

Jiaozi Wang [1], Mats H. Lamann [1], Jonas Richter [2], Robin Steinigeweg [1], Anatoly Dymarsky [3,4,5], and Jochen Gemmer[1]

[1] Department of Physics, University of Osnabrück, D-49076 Osnabrück, Germany
[2] Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, United Kingdom
[3] Moscow Institute of Physics and Technology, 9 Institutskiy pereulok, Dolgoprudny 141701, Russia
[4] Skolkovo Institute of Science and Technology, Skolkovo Innovation Center, Moscow 121205, Russia
[5] Department of Physics, University of Kentucky, Lexington, Kentucky 40506, USA

The eigenstate thermalization hypothesis explains the emergence of the thermodynamic equilibrium in isolated quantum many-body systems by assuming a particular structure of the observable's matrix elements in the energy eigenbasis. Schematically, it postulates that off-diagonal matrix elements are random numbers and the observables can be described by random matrix theory (RMT). To what extent a RMT description applies, more precisely at which energy scale matrix elements of physical operators become truly uncorrelated, is, however, not fully understood. We study this issue by introducing a novel numerical approach to probe correlations between matrix elements for Hilbert-space dimensions beyond those accessible by exact diagonalization. Our analysis is based on the evaluation of higher moments of operator submatrices, defined within energy windows of varying width. Considering nonintegrable quantum spin chains, we observe that matrix elements remain correlated even for narrow energy windows corresponding to timescales of the order of thermalization time of the respective observables. We also demonstrate that such residual correlations between matrix elements are reflected in the dynamics of out-of-time-ordered correlation functions.

[1] J. Wang, M. H. Lamann, J. Richter, R. Steinigeweg, A. Dymarsky, and J. Gemmer, Phys. Rev. Lett. **128**, 180601 (2022).

Raz: The Mpemba Effect through a phase transition

Oren Raz [1], Roi Holtzman [1]

[1] *Weizmann Institute of Science, Rehovot, Israel*

The Mpemba effect describes the situations where a hot system cools faster than an identical copy of the same system initiated at a lower temperature, when both are quenched into a cold environment. In many of the experimental observations of the effect, e.g., in water, clathrate hydrates and some magnetic alloys, the effect is defined by the phase transition timing. However, none of the theoretical investigations on the Mpemba effect so far considered the timing of the phase transition, and most of the abstract models used to explore the Mpemba effect do not have a phase transition.

We suggest a new definition for the time at which the phase transition happens, based on the stability of the disordered phase. We then demonstrate in the mean-field and 2D anti-ferromagnet Ising models that with our definition, the phase transition can indeed happen at a finite, non-zero time after the temperature quench. We then use this phase transition timing to define the Mpemba effect as the situation where the time to phase transition is shorted for the initially hot system, and construct a simple Landau theory example that demonstrates this effect.

[1] “Landau Theory for the Mpemba Effect Through Phase Transitions”, R. Holtzman, O. Raz, arXiv:2204.03995 .

Many-body systems out of equilibrium: recent advances and future directions

Strasberg: Pure state nonequilibrium dynamics and thermodynamics of slow observables

Philipp Strasberg

Grup d'Informació Quàntica, Universitat Autònoma de Barcelona, Spain

It is a fact that a wide range of processes in nonequilibrium and stochastic thermodynamics is described by a Markovian classical rate master equation obeying local detailed balance. Yet, a first principle justification of these three main characteristics - Markovianity, classicality and local detailed balance - has not been given so far. Here, we provide such a justification by combining tools from the eigenstate thermalization hypothesis and typicality based on the assumption that the observable is slow and coarse. Specifically, in this talk I sketch a derivation of these results, discuss the physical picture behind it and in particular the crucial role played by the slowness and coarseness of the observable, elucidate the consequences of local detailed balance, and present numerical results supporting our ideas.

Buča: Non-stationary quantum many-body dynamics

Berislav Buča

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Non-stationary processes are special types of non-mixing dynamics characterised by long-time deterministic dynamics. They are ubiquitous in the real world around us - from biological to social phenomena. Likewise, on the quantum level, any successful long circuit depth calculation on a quantum computer is, by definition, non-stationary. Therefore, understanding how non-stationarity emerges from the microscopic quantum laws is of fundamental scientific and technological importance. I will discuss simple algebraic conditions that prevent a quantum many-body system from ever reaching a stationary state, not even a non-equilibrium one. I give several physically relevant examples in both closed and open quantum many-body systems, including an XXZ spin chain in a strong tilt field, a spin-1/2 Creutz ladder with oscillating out-of-time-order correlators, a spin-dephased Fermi-Hubbard model, and a two-component BEC in a lossy optical cavity which was recently experimentally studied.

Many-body systems out of equilibrium: recent advances and future directions

Richter: Transport, entanglement dynamics, and localization in random quantum circuits

Jonas Richter [1]

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Random quantum circuits provide a useful lens on the universal features of quantum dynamics far from equilibrium. Such circuits are particularly attractive in the context of noisy intermediate-scale quantum (NISQ) devices, where they found applications for instance to strive for a quantum computational advantage and to explore quantum information scrambling. In this talk, I will discuss various examples which highlight the practical relevance of random circuits in the NISQ era and their versatility to explore challenging questions in nonequilibrium many-body quantum systems. I will propose a NISQ algorithm to study quantum hydrodynamics based on the buildup of spatiotemporal correlation functions in quantum spin systems, which leverages random circuits within the framework of quantum typicality. Furthermore, I will introduce a class of long-range random Clifford circuits with global spin conservation, where the emerging transport behavior varies depending on the exponent which controls the probability of gates spanning a certain range. Given their efficient classical simulability even for large system sizes, such circuits provide an ideal framework to study the slowdown of higher Rényi entropies in quantum systems with conservation laws. Finally, I will consider a time-periodic Floquet circuit composed of random Clifford gates, which displays a strong form of localization in one dimension, but shows delocalized dynamics in higher dimensions. The presence (absence) of localization is visualized by numerical simulations of operator spreading, entanglement growth, and of the spectral form factor.

[1] J. Richter and A. Pal, Phys. Rev. Lett. **126**, 230501 (2021). [2] O. Lunt, J. Richter, and A. Pal, arXiv:2112.06682.
[3] J. Richter, O. Lunt, and A. Pal, arXiv:2205.06309.
[4] T. Farshi, J. Richter, *et al*., in preparation.

De Roeck: (Quasi-)Localisation

Wojciech De Roeck [1]

[1] Theoretical Physics Institute, K.U. Leuven, Leuven, Belgium

I will talk about some recent results on quasi-localisation in many-body systems. Most likely about the following topic: In a series of works, it was numerically observed that disordered classical systems like the disordered Klein-Gordon equation or the Nonlinear Schrödinger equation exhibit wavepacket spreading where the width of the wavepacket grows as $t^{1/3}$ with t being time. In such systems there is a tension between Anderson localization of the underlying harmonic system and interactions, arguably bringing about delocalization. This clearly leads to slow spreading of wavepackets but the $t^{1/3}$ law seems to underestimate the power of localization. We try to clarify the situation by a combination of rigorous results and numerics. Our conclusion is that spreading should indeed be much slower, slower than as $t^{1/n}$ for any natural n.

Many-body systems out of equilibrium: recent advances and future directions

Gross: Programmable quantum spin models with Rydberg arrays

Christian Gross

Physikalisches Institut,Tübingen University

Rydberg atoms in optical tweezers offer a novel and versatile platform to realize largely tunable quantum spin models. One and two-dimensional arrays of freely definable geometry can be realized routinely. The interaction between the spins can be spatially and temporally controlled by tailored laser or microwave pulses. This makes this platform an ideal choice to study many-body dynamics in synthesized quantum systems. Here we review the current state of the art of this experimental platform with a focus on milestone experiments on many-body dynamics. We discuss new developments in interaction control and discuss how they can be used to explore novel non-equilibrium many-body physics in the future.

Rosch: Archimedean screw in a chiral magnet

Achim Rosch

Institute for Theoretical Physics, University of Cologne, Germany

When a system with a Goldstone mode is continuously driven, generically the Goldstone mode is “activated” and obtains a linear time dependence. As an example, we study a helical magnet where an oscillating homogeneous magnetic field induces a net rotation of the magnetic texture. This rotation is reminiscent of the motion of an Archimedean screw. This non-linear effect arises for arbitrarily weak oscillating field as long as pinning by disorder is absent. The Archimedean screw can be used to transport spin and charge and thus the screwing motion is predicted to induce a voltage parallel to q. Using a combination of numerics and Floquet spin wave theory, we show that the helix becomes unstable upon increasing the driving field, forming a “time quasicrystal” which oscillates in space and time for moderately strong drive.

[1] Nina del Ser, Lukas Heinen, Achim Rosch, SciPost Phys. 11, 009 (2021)

Hopjan: Behavior of spectral form factor and survival probability in disordered systems

Miroslav Hopjan [1], Lev Vidmar [1,2]

[1] Jožef Stefan Institute, Department for Theoretical Physics, Ljubljana, Slovenia

[2] Department of Physics, Faculty of Mathematics and Physics, University of Ljubljana, Ljubljana, Slovenia

We investigate the behavior of spectral statistics in disordered systems with delocalisation-localisation transitions. Recently it was shown, in the 3D Anderson model [1] and so-called quantum sun model [2], that the spectral form factor and the Thouless time extracted from the spectral form factor are useful measures for characterisation of delocalisation-localisation transition. However, an alternative definition of the Thouless time was given in terms of survival probability [3,4]. Motivated by this fact, we investigate connections of the spectral form factor measure with the survival probability measure and study changes of their behavior across the delocalisation-localisation transitions. We show that both quantities are useful tool for detection of the transitions.

[1] J. Šuntajs, T. Prosen and L. Vidmar, Annals of Physics **435**, 168469 (2021)

[2] J. Šuntajs and L. Vidmar, Phys. Rev. Lett. **129**, 060602 (2022)

[3] M. Schiulaz, E. J. Torres-Herrera, and L. F. Santos, Phys. Rev. B **99**, 174313 (2019)

[4] T. L. M. Lezama, E. J. Torres-Herrera, F. Pérez-Bernal, Y. Bar Lev, and L. F. Santos, Phys. Rev. B **104**, 085117 (2021)

Šuntajs: Ergodicity Breaking Transition in Zero Dimensions

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It is of great current interest to establish toy models of ergodicity breaking transitions in quantum many-body systems. Here, we study a model that is expected to exhibit an ergodic to nonergodic transition in the thermodynamic limit upon tuning the coupling between an ergodic quantum dot and distant particles with spin-1/2. The model is effectively zero dimensional; however, a variant of the model was proposed by de Roeck and Huveneers to describe the avalanche mechanism of ergodicity breaking transition in one-dimensional disordered spin chains. We show that exact numerical results based on the spectral form factor calculation accurately agree with theoretical predictions, and hence unambiguously confirm existence of the ergodicity breaking transition in this model. We benchmark specific properties that represent hallmarks of the ergodicity breaking transition in finite systems.

[1] Phys. Rev. Lett. **129**, 060602 (2022).

Many-body systems out of equilibrium: recent advances and future directions

Heyl: Active quantum flocks

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Flocks of birds or fish represent one of the paradigmatic examples of collective motion in the macroscopic world. Flocks belong to the class of active matter systems, which can be found across various scales ranging from swarms of animals on a macroscopic level down to mesoscopic and microscopic scales such as cellular tissues and bacterial colonies. It has remained, however, a central open question whether active matter such as flocks can also form on even smaller scales where the dynamics are governed by the laws of quantum mechanics. Can also quantum particles form flocks? In this talk I will introduce a model of active particles on a one-dimensional lattice forming a quantum flock, which emerges as a consequence of the spontaneous breaking of an underlying Z_2 symmetry. We find that the resulting active steady state experiences distinct quantum features with the flock exhibiting strong long-range quantum coherence implying. We argue that the identified underlying mechanism is general and can be used to realize also other phases of active quantum matter.

Schiro: Unraveling Quantum Many Body Dynamics

Marco Schiro'

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I will discuss the problem of a quantum many-body system evolving under its own Hamiltonian and subject to local weak quantum measurements. The resulting quantum many-body trajectories evolve according to a stochastic Schrodinger equation. Averaging the wave function over the realisations of the stochastic process gives rise to a Lindblad master equation for the density matrix, which often leads to heating and to featureless stationary states. However, hidden in the random fluctuations of the measuring process there is a much richer physics - with new dynamical phases characterised by qualitatively different entanglement properties and sharp phase transitions between them -which has started to be explored only very recently. I will discuss this measurement-induced criticality in the context of a Quantum Ising Chain [1,2], which I will show to display a transition from a critical phase with logarithmic scaling of the entanglement entropy to an area-law phase corresponding to the onset of the Quantum Zeno Effect. I will argue how the essential features of this problem can be understood by looking at the associated non- Hermitian Hamiltonian and its spectral transition [3]. I will substantiate this idea with a phenomenological quasiparticle picture for the entanglement growth in systems with measurements [4].

[1] A. Biella, M. Schiro', Quantum 5, 528 (2021)
[2] X. Turkeshi, A. Biella, R. Fazio, M. Dalmonte, M. Schiro' Phys. Rev. B 103, 224210 (2021)
[3] X. Turkeshi, M. Schiro', arXiv:2201.09895
[4] X. Turkeshi, R. Fazio, M. Dalmonte, M. Schiro' Phys. Rev. B 105 L241114 (2022)

Many-body systems out of equilibrium: recent advances and future directions

Bar Lev: Absence of localization in interacting spin chains with a discrete symmetry

Benedikt Kloss, Jad C. Halimeh, Achilleas Lazarides, Yevgeny Bar Lev

Ben-Gurion University of the Negev

In this talk, I will present a proof of delocalization in spin chains symmetric under a combination of mirror and spin-flip symmetries and with a nondegenerate spectrum. The proof applies to two prominent examples: the Stark many-body localization system (Stark-MBL) and the symmetrized many-body localization system (symmetrized–MBL). I will also provide numerical evidence of delocalization at all energy densities in these models and show that the delocalization mechanism appears robust to weak symmetry breaking.

arXiv:2208.13793

Mierzejewski: Restoring ergodicity in a strongly disordered interacting chain

Lev Vidmar [1], Bartosz Krajewski [2], Janez Bonča [1,3], Marcin Mierzejewski [2]

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We consider a chain of interacting fermions with random disorder that was intensively studied in the context of many-body localization. We show that only a small fraction of the two-body interaction represents a true local perturbation to the Anderson insulator [1]. While this true perturbation is nonzero at any finite disorder strength *W*, it decreases with increasing *W*. This establishes a view that the strongly disordered system should be viewed as a weakly perturbed integrable model, i.e., a weakly perturbed Anderson insulator. As a consequence, the latter can hardly be distinguished from a strictly integrable system in finite-size calculations at large *W*. We then introduce a rescaled model in which the true perturbation is of the same order of magnitude as the other terms of the Hamiltonian, and show that the system remains ergodic at arbitrary large disorder. Finally, we demonstrate that the approach based on the perturbed Anderson insulators explains rich phenomenology of the spectral functions, which ranges from the anomalous ≈ 1/ω behavior at moderate disorders to more complicated functional forms at strong disorder [2]. The anomalous dynamics originates from that the Anderson LIOMs acquire finite relaxation times due to many-body interaction, i.e., they may become delocalized.

[1] B. Krajewski, L. Vidmar, J. Bonča, M. Mierzejewski, *to be published.*

[2] L. Vidmar, B. Krajewski, J. Bonča, M. Mierzejewski, Phys. Rev. Lett. 127, 230603 (2021)

Herbrych: Quasiballistic transport within long-range anisotropic Heisenberg model

Jacek Herbrych [1], Jakub Wronowicz [1], Marcin Mierzejewski [1]

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Transport in integrable strongly-correlated systems has a ballistic component that coexists with the regular response at nonzero frequencies. While integrability of quantum chains is already rare and requires fine-tuning of parameters, a purely ballistic transport is rare even among integrable systems. By studying the Heisenberg chain with the power-law exchange $J \propto r^{-\alpha}$, where r is a distance, we show that for spin anisotropy $\Delta \simeq \exp(-\alpha + 2)$ the system exhibits a ballistic spin transport up to extremely long times $10^3/J$. This conclusion is reached on the base of the dynamics of spin domains, the dynamical spin conductivity, and via inspecting the matrix elements of the spin-current operator. Our results smoothly connect two models where fully ballistic transport is present: free particles with nearest-neighbor hopping and the isotropic Haldane-Shastry model.

Bonča: Relaxation dynamics and fluctuation analysis in a strongly disordered system

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Wrocław University of Science and Technology, 50-370 Wrocław, Poland

I will discuss the interplay between many-body localization and spin-symmetry. I will present the time evolution of several observables in the anisotropic t – J model. Like the Hubbard chain, the studied model contains charge and spin degrees of freedom. Yet, it has a smaller Hilbert space and thus allows for numerical studies of larger systems. I will compare the field disorder that breaks the Z_2 spin symmetry and a potential disorder that preserves the latter symmetry [1]. In the former case, sufficiently strong disorder leads to localization of all studied observables, at least for the studied system sizes. However, in the case of symmetry-preserving disorder, we observe that odd operators under the Z_2 spin transformation relax towards the equilibrium value at relatively short time scales that grow only polynomially with the disorder strength. On the other hand, the dynamics of even operators and the level statistics within each symmetry sector are consistent with localization. Our results indicate that localization exists within each symmetry sector for symmetry preserving disorder. Odd operators' apparent relaxation is due to their time evolution between various symmetry sectors.

In the second part [2] I will present the analysis of sample-to-sample fluctuations of the gap ratio in the energy spectra in finite disordered spin chains. We show that fluctuations are correctly captured by the Rosenzweig-Porter (RP) model only away from the ergodic-nonergodic crossover regime. Upon introducing an extension to the RP model, one correctly reproduces the fluctuations in all regimes, i.e., in the ergodic and nonergodic regimes as well as at the crossover between them. Finally, we demonstrate how to reduce the sample-to-sample fluctuations in both studied microscopic models.

[1] Janez Bonca and Marcin Mierzejewski, *Relaxation mechanisms in a disordered system with Poisson-level statistics,* Phys. Rev. B **105**, 155146 (2022).

[2] Bartosz Krajewski, Marcin Mierzejewski, and Janez Bonca, *Modeling sample-to-sample fluctuations of the gap ratio in finite disordered spin chains,* Phys. Rev. B **106**, 014201 (2022).

Sels: Golden rule and avalanches in disordered 1D spin chains

Dries Sels

Arts and Science, New York University

In this talk I will discuss recent numerical results regarding the stability of the many-body localized regime in 1D. The discussion will be centered around two recent works [1,2]. I will argue that, on the ergodic side, the onset of localization is governed by the Fermi golden rule relaxation rate approaching the level spacing. Similarly, on the localized side, the bath-induced relaxation rate ought to be small enough to avoid avalanches. I will show that a large regime of disorder strengths, previously believed to be rather deep in the MBL phase, is in fact ergodic. I will present a recursive construction of local integrals of motion (lioms) at asymptotically large disorder and show that such construction yields a finite lifetime for the lioms, consistent with Fermi's golden rule.

[1] Dries Sels, Bath-induced delocalization in interacting disordered spin chains, Phys. Rev. B 106, L020202 (2022)

[2] Dries Sels, Anatoli Polkovnikov, Thermalization of dilute impurities in one dimensional spin chains, arXiv:2105.09348 (2021)