Breakdown of ergodicity in quantum systems: from solids to synthetic matter

Introduction

Ergodicity is a fundamental property of many physical systems which reflects their ability to reach thermal equilibrium during the course of dynamical evolution. In recent years, it has been understood that exceptions to this fundamental behaviour may be possible: as particles become localised by the external disorder, they can fail to form a thermal environment for themselves. Such “many-body localised” (MBL) systems are perfect insulators, unlike the more familiar band or Mott insulators. That is, the (electrical) conductivity of an MBL system is precisely zero not only in its ground state, but also at finite energy densities, where in ordinary insulators thermally activated transport would dominate. These, along with many other unique properties, have led to an explosion of recent interest in understanding MBL systems, as well as more general, non-ergodic behaviours of quantum many-body systems. What would such systems do, if they do not approach a thermal state? Are there universal aspects to this behaviour, or will every system behave in a different way? On the more applied side, MBL might open a new strategy for fighting decoherence. In all current quantum computing attempts, the main difficulty results from the fact that the thermal environment tends to thermalise a qubit, thereby causing decoherence. This has the unwanted consequence of information scrambling: during thermalisation, quantum information encoded in the initial state will spread over the entire system and thereby become inaccessible to local measurements. This may not be the case in MBL systems: as a localised environment fails to thermalise, the system can retain some local information about its initial state for indefinite amounts of time, opening up new possibilities for quantum technologies.

History

Originally proposed by Anderson in 1958 [1], disorder-induced localisation was initially mostly studied as a single-particle phenomenon – dubbed Anderson localisation. As a paradigmatic quantum phenomenon, Anderson localisation results from the destructive interference between many scattered waves, which localise a quantum particle and hinder transport. The open question for many decades was whether this single-particle effect survives in interacting systems, or whether interactions, in the form of scattering between localised orbitals, invariably spoil this picture by restoring transport and thermalisation. Starting with seminal works in 2005 by Basko, Aleiner, and Altshuler [2] and Gornyi, Mirlin, and Polyakov [3], this topic has attracted renewed interest. Over the following years, the existence of MBL phases in the presence of interactions and finite energies were demonstrated numerically using exact simulations of one-dimensional quantum lattice models [4]. This has paved the way to a phenomenological picture of MBL systems known as “Local Integrals of Motion” [5,6], which was rigorously proven (under certain physically reasonable assumptions) by Imbrie [7]. These efforts have led to a rather complete theoretical understanding of MBL phases and their unique properties (such as the logarithmic spreading of entanglement in a global quench [8]) in one dimensional, strongly-disordered interacting models.

Experiments

On the of the main challenges lies in the fact that a MBL system can only be stable in perfect isolation form any thermal environment, since otherwise the environment will, in the long term, always thermalise the system. The main experimental workhorses for studying MBL have been synthetic many-body systems such as ultracold atoms [9] and trapped ions [10], which are naturally well-isolated from the environment. While trapped ion systems are intrinsically limited in system size, and cold atoms in optical lattices only allow for limited observation time, these systems could nonetheless demonstrate many fundamental aspects of MBL, in particular the local memory of the system's initial condition. Furthermore, there have also been indications of MBL in disordered two-dimensional superconducting films [11] and similar behaviours of very slow relaxations have been observed in NV centres in diamond [12]. Very recent experiments [13, 14] have begun to probe new types of quantum orders that are protected by MBL and cannot exist in thermal equilibrium, such as the discrete time crystal — a novel phase of matter that spontaneously breaks time-translation symmetry.

This volume

One topic that was featured prominently in the meeting is the stability of MBL to local thermal inclusions. In the presence of truly random disorder, there are always rare regions where the disorder is weaker than average, which constitute a thermal inclusion (Griffiths region). What are the consequences of such "hot" regions nucleated in the MBL phase? This was investigated in a toy model by Chandran *et al.*, while general consequences of such non-perturbative effects are reviewed by de Roeck and Imbrie, who argue that thermal inclusions will cause destabilisation of MBL in dimensions higher than one.

The article by Torres-Herrera and Santos studies the dynamical properties of quantum chaotic systems. They demonstrate that the resulting correlation hole in the survival probability can be used as a general indicator of the integrable-chaotic transition in disordered and clean models. This method could therefore potentially be used in experiments to detect the transition to the MBL phase in disordered interacting systems.

Another aspect of current research is the connection between MBL and quantum integrable systems. Both are characterised by an unusually large number of conserved operators; the operators are exponentially localised in the case of MBL, and are a sum of local terms in the case of quantum integrable models such as the XXZ spin chain, the 1D Fermi Hubbard chain or 1D Bose gases with contact interactions. The discussion paper by Moore reviews the recent progress in formulating the emergent hydrodynamic description of such models, while the article by Essler *et al.* uses the integrability of the 1D Hubbard model to demonstrate that it harbours eigenstates with unusual entanglement properties at arbitrarily high energies, signifying a possible non-thermal phase called "quantum disentangled liquid".

The present volume also reports several advances in classical and quantum computation with MBL states. In particular, Devakul *et al.* present benchmarks for DMRG-X, an extension of matrix product state methods capable of targeting highly-excited eigenstates of MBL systems, while Mossi and Scardicchio study the dynamics of disordered quantum spin systems on the Bethe lattice and draw connections to the analysis of the performance of quantum adiabatic algorithms.

On the experimental side, this volume contains a review by Hess *et al.* on exploring non-ergodic phenomena in long-range interacting spin models realised by trapped ions. They observe a long-lived local memory of the out-of-equilibrium initial conditions and signatures of time crystal in the presence of quenched disorder. On the cold atom side, D'Errico *et al.* review recent work on microscopic dissipation by the creation of phase slips in 1D Bose-Hubbard systems.

Open Questions

The many contributions of the workshop, along with the manuscripts published in this volume, provide a fairly comprehensive picture of the theoretical and experimental status of MBL and non-ergodic quantum systems as of 2017. While remarkable theoretical and experimental progress has been made in understanding the properties of one-dimensional strongly-disordered systems in the presence of interactions, there also remain several open problems.

The main challenges concern the understanding of the MBL transition and stability of MBL phases in higher dimensions. These are difficult questions because they require studies of large systems and dynamics at long times, which remain a challenge for both theory and experiment. For example, the exponential increase in Hilbert space dimension and volume-law entanglement (typical of thermalising systems) present an obstacle for both exact and variational numerics, as well as for present-day trapped ion systems. In cold atom experiments, on the other hand, larger system sizes can be reached, but the long-time dynamics become dominated by experimental imperfections and couplings to the outside world, which eventually destroy MBL. Another open question includes similarities and differences between truly random disorder and quasi-random potentials, such as employed in many experiments.

Furthermore, several connections to quantum integrable systems (such as Bethe Ansatz solvable 1D models) and other non-ergodic systems, such as classical glasses, need better understanding. Another mostly uncharted territory is the possible connection between the quantum effects of MBL and the distinctly classical non-ergodic dynamics of structural glasses. Are these phenomena related in any meaningful sense, and will it be possible to observe MBL, or MBL-like phenomena, also in the absence of quenched disorder?

Conclusion

Recent years have witnessed a very exciting time in many-body physics, with the rekindled interest in localisation inspiring us to rethink the basic notions of thermalisation, information scrambling, decoherence and many other related phenomena. It will be fascinating to follow this progress fully unfold, possibly leading to new theoretical breakthroughs in quantum statistical physics, information theory and practical applications of non-ergodic quantum systems.

Thanks

The authors are grateful for the administrative support provided by the staff of the Royal Society for both the discussion meeting and the preparation of this volume. They also thank all the valuable contributions made by the speakers/authors, and those who contributed to valuable discussions at the meeting.

References

[1] P. W. Anderson, Phys. Rev. **109**, 1492 (1958).

[2] D. Basko, I. Aleiner, and B. Altshuler, Annals of Physics **321**, 1126 (2006).

[3] I. V. Gornyi, A. D. Mirlin, and D. G. Polyakov, Phys. Rev. Lett. **95**, 206603 (2005).

[4] A. Pal and D. A. Huse, Phys. Rev. B **82**, 174411 (2010).

[5] M. Serbyn, Z. Papic, and D. A. Abanin, Phys. Rev. Lett. **111**, 127201 (2013).

[6] D. A. Huse, R. Nandkishore, and V. Oganesyan, Phys. Rev. B **90**, 174202 (2014).

[7] J. Z. Imbrie, Journal of Statistical Physics **163**, 998 (2016).

[8] J. H. Bardarson, F. Pollmann, and J. E. Moore, Phys. Rev. Lett. **109**, 017202 (2012).

[9] M. Schreiber *et al.*, Science **349**, 842 (2015).

[10] J. Smith *et al.*, Nat. Phys. **12**, 907 (2016).

[11] M. Ovadia *et al.*, Scientific Reports **5**, 13503 (2015).

[12] G. Kucsko *et al.*, arXiv:1609.08216.

[13] S. Choi *et al.,* Nature **543**, 221 (2017).

[14] J. Zhang *et al.*, Nature **543**, 217 (2017).