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Report on the PhD Thesis submitted by Adith Sai Aramthottil

Field of research, motivation and goals

The thesis titled *Towards understanding of non-ergodic physics in quantum many body systems* submitted by Adith Sai Aramthottil addresses timely questions at the interface of quantum many-body physics, condensed matter theory and quantum simulation. Specifically, the author is interested in the nonequilibrium dynamics of closed quantum many-body systems, related to the emergence of thermalization, and thus addressing basic questions of the nonequilibrium statistical physics of quantum many-body systems. The current main pillar for our understanding of thermalization in closed quantum systems is the eigenstate thermalization hypothesis (ETH) that provides sufficient criteria. A system is called ergodic if it meets these ETH criteria. The main interest of the thesis is in exceptions, that is, systems, that are weakly or strongly ergodicity breaking. In the latter category, the best studied candidate is many-body localization (MBL), while recent research has identified system with quantum scars or Hilbert-space fragmentation (HSF) as instances of weakly nonergodic systems. Crucial open questions in the field relate to: (i) the stability and existence of MBL in non-standard disorder potentials, (ii) stability and experimental realizations of quantum scars, (iii) conditions for the emergence of HSF in realistic experimental platforms. This theoretical thesis makes contributions to these three key questions using a range of theoretical tools, in particular, computational methods.

While the thesis is theoretical, the thesis partially takes its motivation from specific realistic experimental set-ups. The relevant experimental platforms are quantum simulators based on cold atoms or molecules in optical lattices including Rydberg atom systems.

Results

The thesis contains results that were published in four articles in peer-reviewed journals, all of the highest international standard, including two letter-style publications. Aramthottil is the first author for all four publications.

The first article PRB 106, L041101 (2022) investigates the emergence of quantum scar states in a model for a Z_2 lattice gauge theory (LGT), dubbed gauged Kitaev chain. By using a mapping to a quantum Ising model with longitudinal and transversal fields, parameter regions with violations of quantum-chaos expectations are identified using exact-diagonalization methods. Furthermore, the model has an effective Hamiltonian for which scar states are known in limiting cases. This allows the authors to follow the evolution and stability of the scar states as Hamiltonian parameters are varied. Two types of scars exist, characterized by either low entanglement or high entanglement. The fingerprints of scars in the time evolution of the fidelity is investigated as a dynamical probe. This work establishes an example of a LGT in which scar states exist in its deconfined phase, thus suggesting that charge confinement is not necessary for the emergence of scars. Thus, a relevant and qualitatively new result was reported in this article.

The 2nd article PRB 107, 104305 (2023) studies a model system based on polar lattice bosons. Here, long-range interactions play a role and typically, density-dependent tunneling is present with a sizable pre-factor compared to other terms of the Hamiltonian. The goal of the article is to elucidate the role of this density-dependent tunneling on spectral statistics as measured by gap ratio, entanglement entropy and time-dependent observables that are accessible in experiments. The article contains two key results: (i) density-dependent tunneling in general leads to delocalization and (ii) can, for fine-tuned parameters, lead to a splitting of the Hilbert space into ergodic and non-ergodic sectors, reminiscent of Hilbert-space fragmentation. These results add to the current understanding of the various competing terms in the Hamiltonian of polar lattice bosons that encompasses rich physics in equilibrium and nonequilibrium. In particular, the results may guide future experiments that aim at revealing the effect of density-dependent tunneling (which is absent in most experiments with cold atoms that feature only local Hubbard interactions). The results are obtained using mostly exact diagonalization, compared to a mean-field theory analysis.

The third article PRB 104, 214201 (2021) addresses a very important open question from the field of many-body localization. The existence and stability of MBL in the presence of uncorrelated onsite disorder with a finite-width distribution is controversially discussed, yet some of the counterarguments against the stability of MBL cannot apply to systems with quasi-periodic disorder (e.g., the avalanche mechanism). Hence, such systems may be better candidates to obtain a stable MBL phase and such quasi-periodic potentials are readily present in many quantum-simulator experiments. In previous literature, differences between these two cases were not so obvious in finite-system size computational studies. In this article, Aramthottil et al. succeed in identifying clear differences between full random disorder and quasi-periodic systems. These include properties of the density distributions even on the ergodic side and a weaker trend towards delocalization compared to random disorder distributions. The analysis is

carried out with state-of-the-art exact-diagonalization methods (in particular, the POLFED method) and utilizes recently proposed concepts of cost functions for determining optimum scaling collapses in a finite-size scaling analysis. Qualitatively, a better agreement with a Berezinskii-Kosterlitz-Thouless scaling is reported rather than with a power-law behavior. In my assessment, this work is the key result from the thesis since first, it addresses a quite basic and important question in the field and provides important new insights and second, it has a high potential to stimulate follow-up work.

While the previous study considered onsite disorder, the fourth article turns to bond disordered spin chains (PRL 133, 196302 (2024)). Such disorder is actually usually more common in solid-state environments but considerably less well studied than random onsite disorder. For instance, the finite-size state diagrams of delocalization-localization transitions are only partially known, and more importantly, the effective description is likely not based on so-called l-bits, the quasi-local conserved charges relevant in standard MBL. This article addresses this latter question and employs a real-space renormalization group scheme to obtain a phenomenological picture of the eigenstate properties of such systems (with broken $SU(2)$ symmetry) with a power-law decay of the coupling constants (motivated by experimental systems with Rydberg atoms). As a main result, the absence of an l-bit description is supported by this analysis valid at strong disorder. This work makes an important contribution since finding novel forms of MBL beyond MBL systems with an l-bit description is a key open question. Moreover, the class of experimental systems with bond disorder is large and this work specifically contributes to the understanding of Hamiltonians relevant for Rydberg systems.

Accompanying text in the thesis

The accompanying text provides a very good and compact introduction and puts the four main results into their broader context and explains their connection in the framework of ergodic, non-ergodic and weakly non-ergodic systems. Relevant literature and crucial theoretical concepts are provided. Perhaps a discussion of the available theoretical tools would have been useful as an optional addition, yet overall, the accompanying text is well written.

Final assessment

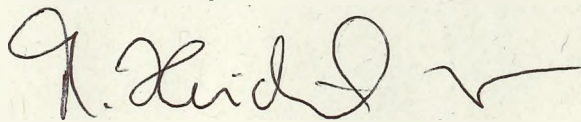
With this thesis, Adith Sai Aramthottil has convincingly demonstrated their ability to carry out independent theoretical research at the forefront of quantum many-body physics of lattice systems. All four papers make relevant and novel contributions to the field. For a PhD thesis, the papers cover a quite broad range of timely topics from quantum scars to two variants of disorder. At least two publications take their motivation from specific experimental systems, while some others are of more conceptual nature. Thus, the thesis reflects a balanced selection of topics, and important in condensed matter theory, makes contact to experiments. The publications reflect a comprehensive knowledge of the relevant literature. In particular, a range of state-of-the-art theoretical tools was used and mastered by Aramthottil, including standard exact-diagonalization techniques, mean-field theory as well as state-of-the-art computational such as POLFED but also renormalization group schemes. The thesis and its accompanying

publications demonstrate that Adith Sai Aramthottil is a mature and independent scientist with a very good understanding and knowledge of the theoretical concepts in the thesis' discipline, is aware of relevant open questions in the field, and masters a quite impressively large range of theoretical tools.

The thesis meets all standard criteria for a PhD thesis for sure. In terms of the quality of the research (in particular, as evidenced by the third and fourth article), the wealth of results, and mastery of theoretical tools, the thesis is way beyond average. I therefore recommend that the Faculty of Physics accept the thesis and that the candidate may proceed to the oral defense. Given the very high quality of the scientific work documented here, I recommend that this work be graded as

with distinction.

Yours sincerely,

A handwritten signature in dark ink, appearing to read 'F. Heidrich-Meisner', followed by a long horizontal flourish.

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