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Dynamics and Thermodynamics of Many Particle Cold Atom Systems

Anatoli Polkovnikov
TRUSTEES OF BOSTON UNIVERSITY

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14. ABSTRACT

The focus of this proposal was theoretical research on various non-equilibrium phenomena in isolated quantum systems and applications to experimental setups largely to cold atoms. All goals stated in the proposal were addressed. In addition two conceptually new ideas have emerged (Floquet systems and application of phase space methods to strongly interacting systems). These ideas were partly addressed in recent publications and partly they underlined the renewal proposal of this grant. Overall this grant resulted in seventeen published papers including three reviews (one published in Advances in Physics, one invited review submitted to Advances in Physics and one review to be shortly submitted to Physics Reports), one paper in Nature and four papers in Physical Review Letters. There are several more preprints posted on arXiv in 2015, which should be published soon/ Results of this work were presented on numerous (over fifty) invited talks at domestic and international conferences, workshops, schools as well as research Institutions across the world. Also this grant supported active participation of junior collaborators at conferences and

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Listed below are the topics listed in the original proposal, published works relevant to this topic (some publications appear in more than one topic) and a summary highlighting the key results. In addition there is an extra fifth topic (phase space methods for strongly correlated systems), which was not originally anticipated.

1. ***Universal quantum critical dynamics***
   a. *Universal Rephasing Dynamics after a Quantum Quench via Sudden Coupling of Two Initially Independent Condensates***,** E. G. Dalla Torre, E. Demler, A. Polkovnikov, **Phys. Rev. Lett. 110**, 090404 (2013)
   b. *Microscopic theory of non-adiabatic response in real and imaginary time,* C. De Grandi, A. Polkovnikov, A. W. Sandvik, **J. Phys.: Condens. Matter 25**, 404216 (2013) (special issue dedicated to T. Kibble).
   c. *Classifying and measuring the geometry of the quantum ground state manifold,* M. Kolodrubetz, V. Gritsev, A. Polkovnikov, **Phys. Rev. B 88**, 064304 (2013) (editor's pick).
   d. *Dynamic trapping near a quantum critical point,* M. Kolodrubetz, E. Katz, A. Polkovnikov, **Phys. Rev. B 91**, 054306 (2015)
   e. *Slow quenches in a quantum Ising chain; dynamical phase transitions and topology, S. Sharma, U. Divakaran, A. Polkovnikov, A. Dutta,* **arXiv:1601.01637** (accepted to **Phys. Rev. B**).

In these publications several new predictions has been made including prediction of a new type of dynamical trapping phase transitions (**1d**), where it was shown that the systems naturally self-tune themselves to quantum critical regimes and become trapped there. This finding can have many implications from cosmology (explaining to why the Higgs mass is unnaturally small) to condensed matter and cold atom systems predicting that quantum critical dynamics can be very robust without any fine-tuning. Ref. (**1b**) is highly relevant to problems of quantum annealing as it shows that the imaginary time quantum annealing (amenable to quantum simulations using quantum Monte-Carlo methods) is closely related to real time quantum dynamics relevant for quantum simulators and quantum annealers , which can be realized in the lab. Ref. (**1a**) demonstrated that the ideas of universal dynamics are also relevant to quantum quenches realized in many cold atom labs.

2. ***Dynamical response and quantum geometry***
   a. *Microscopic theory of non-adiabatic response in real and imaginary time, C. De Grandi, A. Polkovnikov, A. W. Sandvik**, J. Phys.: Condens. Matter 25**, 404216 (2013) (special issue dedicated to T. Kibble).*
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d. *Dynamic trapping near a quantum critical point,* M. Kolodrubetz, E. Katz, A. Polkovnikov, **Phys. Rev. B 91**, 054306 (2015).

e. *Observation of topological transitions in interacting quantum circuits,* P. Roushan, C. Neill, Yu Chen, M. Kolodrubetz, C. Quintana, N. Leung, M. Fang, R. Barends, B. Campbell, Z. Chen, B. Chiaro, A. Dunsworth, E. Jeffrey, J. Kelly, A. Megrant, J. Mutus, P. O'Malley, D. Sank, A. Vainsencher, J. Wenner, T. White, A. Polkovnikov, A. N. Cleland, J. M. Martinis, **Nature 515**, 241 (2014).

f. *Enabling Adiabatic Passages Between Disjoint Regions in Parameter Space through Topological Transitions,* T. Souza, M. Tomka, M. Kolodrubetz, S. Rosenberg, A. Polkovnikov, **arXiv:1512.05803** (submitted to Phys. Rev. B).

g. *Emergent Newtonian dynamics and the geometric origin of mass,* L. D'Alessio, A. Polkovnikov, **Annals of Physics 345**, 141 (2014).

h. *Geometry and non-adiabatic response in quantum and classical systems,* M. Kolodrubetz, P. Mehta, A. Polkovnikov, **arXiv:1602.01062** (to be submitted to Phys. Reports). (Review).

Based on the theory developed by the PI earlier (supported by the previous AFOSR grant) topological phase transitions were measured for the first time through the dynamical response (the quantized Coriolis force). Particular measurements were performed in superconducting qubits in K. Lehnert's and J. Martinis' groups (**2c**, **2e**). In addition there is an unpublished experiment done in Ian Spielman group (NIST) on cold atom systems, where they extended these ideas to measure the second Chern number in cold atoms for the first time ever (in any system). These results should be published soon. PI and collaborators also proposed a new geometric classification of quantum phase transitions based on the Fubini-Study metric tensor, defined new topological invariants based on the Euler characteristic and proposed the experimental way to measure the metric tensor and the invariants (**2b**). This paper was picked as editors highlight in Phys. Rev. B. It is anticipated that these ideas will be soon implemented by various experimental groups. In Ref. (**2g**) PI and his postdoc developed a general theory of non-adiabatic corrections beyond the Born-Oppenheimer approximation and showed that the mass is closely related to quantum geometry. Also it was shown that the whole formalism of macroscopic Hamiltonian dynamics can be derived from the non-adiabatic expansion and leading non-adiabatic corrections beyond the Hamiltonian dynamic were identified. This work was summarized in a review (**2h**), which was recently posted online and which should be submitted to Physics Reports by May 2016.

3. **Failure of short time expansion and dynamical phase transitions. Floquet systems** (new closely related topic).

    a. *Dynamical Quantum Phase Transitions in the Transverse Field Ising Model*, M. Heyl, A. Polkovnikov, S. Kehrein, **Phys. Rev. Lett. 110**, 135704 (2013).

b. Many-body energy localization transition in periodically driven systems, L. D'Alessio, A. Polkovnikov, **Annals of Physics 333**, 19 (2013).

c. Universal High-Frequency Behavior of Periodically Driven Systems: from Dynamical Stabilization to Floquet Engineering, M. Bukov, L. D'Alessio, A. Polkovnikov, **Advances in Physics 64**, 139 (2015). (Review).

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f. Schrieffer-Wolff Transformation for Periodically Driven Systems: Strongly Correlated Systems with Artificial Gauge Fields, M. Bukov, M. Kolodrubetz, A. Polkovnikov, **Phys. Rev. Lett. 116**, 125301 (2016).

g. Heating and Many-Body Resonances in a Periodically-Driven Two-Band System, M. Bukov, M. Heyl, D. A. Huse, A. Polkovnikov, **arXiv:1512.02119** (accepted to Phys. Rev. B).

h. Slow quenches in a quantum Ising chain; dynamical phase transitions and topology, S. Sharma, U. Divakaran, A. Polkovnikov, A. Dutta, **arXiv:1601.01637** (accepted to **Phys. Rev. B**).

This part of the proposal originally started as a systematic study of short time expansion and resulting dynamical phase transitions and their applications for quenches (**3a**), ramps (**3h**) and Floquet systems **(3b**). The pioneering papers (**3a** and **3b**) resulted numerous follow up work by various groups. Also this work resulted in PI's general interest in Floquet (periodically driven) systems. It was found that the famous Schrieffer-Wolff transformation widely used in condensed matter systems is an example of the short time expansion in the rotating frame (**3f**). It was found that heating in Floquet systems has many parallels with the many-body localizataion transition without disorder and that proliferation of the many-body resonances is responsible for a glass-type heating transition (**3b**, **3g**). PI and his graduate student and postdoc wrote a comprehensive review on Floquet systems and discussed engineering interacting and non-interacting Floquet Hamiltonians in the context of cold atoms (**3c**). This review as well as several other papers mentioned here already generated significant impact and are highly cited.

4. Relaxational dynamics of nearly integrable systems

a. Efficiency bounds for nonequilibrium heat engines, P. Mehta, A. Polkovnikov, **Annals of Phys. 332**, 110-126 (2013)

b. *Universal Rephasing Dynamics after a Quantum Quench via Sudden Coupling of Two Initially Independent Condensates***,** E. G. Dalla Torre, E. Demler, A. Polkovnikov, **Phys. Rev. Lett. 110**, 090404 (2013)
c. From Quantum Chaos and Eigenstate Thermalization to Statistical Mechanics and Thermodynamics, L. D'Alessio, Y. Kafri, A. Polkovnikov, M. Rigol, **arXiv:1509.06411** (Invited review for Advances in Physics).
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Most work on this goal as well as on a broader area of dynamics in quantum chaotic systems resulted in a substantial (over 120 pages) invited review, which was submitted to Advances in Physics and should be published in 2016. This review covered the whole range of topics including quantum chaotic dynamics, the eigenstate thermalization theory and its relation to the random matrix theory, implications of quantum chaos to thermodynamics of isolated systems, dynamics of integrable and nearly integrable systems (**4c**). PI and co-authors attempted to give a comprehensive overview of these topics, which can serve as the basis for further investigation of how inegrability breaks down in many-particle systems. One interesting mechanism of breaking down integrability for FLoquet systems though proliferation of many-body resonances was discussed in Ref. (**4d**). Ref. (**4a**) showed that non-equilibrium steady states, which by definition have lower entropy than thermal states, can be used to develop efficient non-equilibrium heat engines which can beat equilibrium bounds like e.g. the Carnot bound.

5. **Extension of semiclassical phase space methods to strongly interacting systems.**

a. SU(3) semiclassical representation of quantum dynamics of interacting spins, S. M. Davidson, A. Polkovnikov, **Phys. Rev. Lett. 114**, 043603 (2015)

This (together with Floquet systems) was a new topic not originally anticipated in the prior proposal. This work was a breakthrough allowing one to efficiently simulate dynamics of strongly interacting spins systems by extending phase space dimensionality (introducing hidden dimensions) and then applying semiclassical (truncated Wigner type) methods. The developed method was applied to various experimentally relevant cold atoms setups and it was shown that the agreement with experiments and exact diagonalization in small systems is very remarkable probably beating any other available method. In a follow up work soon to be submitted these ideas were extended to strongly interacting fermionic systems for the first time allowing one to simulate their dynamics far from equilibrium. It is likely that these ideas will find many applications in many areas of physics, quantum chemistry and beyond.

Through this project PI supported the following personnel: two graduate students: Marin Bukov and Shainen Davidson, and one Post-Doc: Michael Kolodrubetz. They all contributed to publications acknowledging support by this grant.

In the end of this report I would like to sincerely thank AFOSR for giving me and my group the opportunity to develop new ideas, which hopefully will find many interesting applications.

1.

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Abstract

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