

Topology and dynamics in driven quantum systems

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The discovery of quantum mechanics revolutionized our understanding of matter. While macroscopic bodies behave according to Newton’s laws of motion, microscopic objects follow a completely different set of *quantum mechanical* laws of motion. We now understand that matter may possess some particularly quantum properties, such as *coherence* and *entanglement*. Famously, these properties allow Schrödinger’s cat to be both alive and dead, or a quantum mechanical bit to take both values 0 and 1 at the same time. These remarkable yet fragile properties have been shown theoretically to offer profound increases in computational power over conventional (classical) circuits.

Recent advances have enabled the quantum mechanical properties of matter to be studied in ever larger systems. This opens the way for exploring many intriguing fundamental questions as well as the possibility of transformative practical advances. In particular, a powerful interplay between theory and experiments will allow us to address: What determines the time and length scales over which quantum mechanical behavior may persist? Do the laws of quantum mechanics impose fundamental limitations on the performance of nanoscale electronic systems? Can the quantum behaviors of microchip-scale systems be enhanced and harnessed for novel applications?

Objectives

The aim of “TopDrive” is to open new avenues for exploring and addressing the fundamental questions highlighted above, in the context of solid state and cold atomic systems driven out of equilibrium. We seek to identify and elucidate new types of robust quantum mechanical phenomena that may be realized in these systems using newly available tools for driving and control, such as intense time-dependent laser and microwave fields. Drawing on an analogy with equilibrium systems, topological phenomena in driven systems are expected to be particularly robust, making them exciting candidates for investigating the quantum properties of matter.

i. Topological classification for periodically driven quantum systems

Historically, phases of matter have been classified by the “order,” or types of broken symmetries, that they possess. In a crystal, the uniformity of space is broken by the positioning of atoms, which spontaneously take on a periodic arrangement. In a ferromagnet, electronic spins spontaneously pick a particular direction along which to point. The symmetry-based classification organizes our understanding of phases and phase transitions, and helps to identify *universality* among diverse phenomena which occur in a wide range of both classical and quantum systems.

Recently, another avenue of classification based on the *topological* features of quantum states has emerged. The topological classification of quantum states is more abstract than the symmetry-based classification, often with no simple classical properties associated with the mathematical quantities used to distinguish different phases. However, some of the most robust and profound quantum mechanical phenomena owe their existence to these topological properties.

Although topologically-nontrivial states are rare to find in nature, their remarkable characteristics provide great motivation for their intensive study. Can analogues or new types of such robust topological phenomena be generated dynamically (“on demand”) in driven systems? This would open many exciting new avenues for exploring and utilizing these remarkable effects. Thus we aim to construct a complete classification scheme for topological behavior in non-interacting periodically driven systems, analogous to the highly useful “periodic table of topological insulators.”

ii. Characterization of non-equilibrium dynamics in driven quantum systems

With TopDrive we aim to elucidate the nature of the steady states achieved in periodically driven systems under general driving and system-bath coupling conditions. We furthermore seek to identify relevant experimental observables, or probes, that can be used to identify new behaviors.

Results

Over the course of the project, we have obtained significant results along both lines of investi-

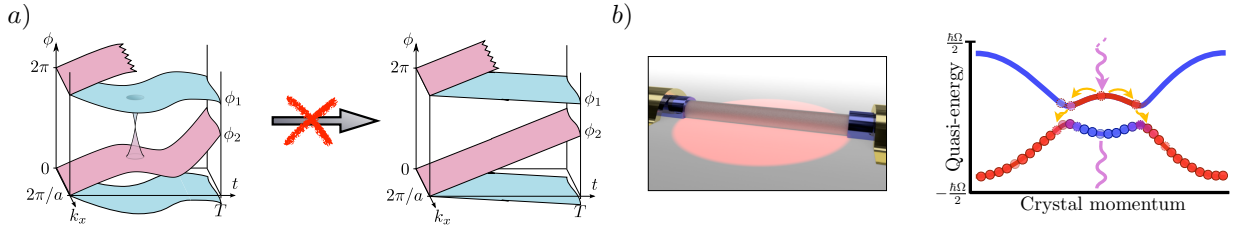


FIG. 1. a) Topological singularities distinguish the evolution of driven and non-driven systems, and provide the basis for topological classification¹. b) In a nanowire driven by a continuous wave laser, an insulator-like steady state is stabilized by coupling to engineered phonon and Fermi reservoirs².

gation outlined above. On the subject of classification, I engaged a local PhD student (Frederik Nathan) in the project. We identified a key new type of “topological singularity” that can occur in the evolution of a driven system, which is not possible in equilibrium. We used these singularities as the basis to develop a framework for classifying topological bands in periodically driven systems¹. This work has already stimulated further activity in the community, and for example will help to develop new quantum control protocols for realizing topological phenomena in driven systems.

On the subject of characterizing non-equilibrium dynamics, we completed a detailed study of steady states of “Floquet topological insulators” in the presence of a dissipative environment. We identified the key factors that control steady state populations, and used this understanding to propose reservoir engineering schemes that can be used to stabilize desired types of non-equilibrium steady states. This work, which involved a combination of analytical and numerical approaches, was performed with an international team of researchers from Caltech (USA) and the Technion Institute of Technology (ISR). Our results are published in Physical Review X².

Building on the synergy between the two parts of the project, we went on to identify new topological quantized observables – *non-adiabatic* quantized charge pumping³ and quantized magnetization density⁴ – that can be used to reveal the unique topology of periodically driven systems. In the latter work, carried out with my PhD student along with collaborators at Caltech (USA), the Technion (ISR), and the Weizmann Institute of Science (ISR), we propose an experiment for detecting the quantized magnetization density in cold atomic gases⁴. On a fundamental level, we expect that these results will yield valuable insight into the classification problem for interacting systems. We also hope that they will stimulate and enable further experimental activity, which will help propel the field forward.

We have also obtained important results for interacting periodically driven systems. First, we found a new type of chiral plasmonic mode that propagates along the edges of two dimensional interacting systems with broken time reversal symmetry⁵. Driving provides means to control the nonreciprocal propagation of such modes “on demand,” with potential applications in optoelectronics. In another work, my collaborators and I found a way to turn heating, usually viewed as one of the biggest obstacles to achieving quantum behavior in driven systems, into a resource for achieving new universal phenomena. In systems where there is a large separation of energy scales, rapid heating of low energy modes may bring the system to a highly randomized state where fine details of the spectrum are washed out and only the universal, topological features remain to be reflected in observables. We demonstrate this principle through the example of a one dimensional system, driven at low frequency, which exhibits a universal pumping current over exponentially long time scales in the appropriate regime⁶.

¹ F. Nathan and M. S. Rudner, New Journal of Physics **17**, 125014 (2015).

² K Seetharam, C.-E. Bardyn, N. Lindner, M. Rudner, and G. Refael, Phys. Rev. X **5**, 041050 (2015).

³ P. Titum, E. Berg, M. S. Rudner, G. Refael, and N. H. Lindner, Phys. Rev. X **6**, 021013 (2016).

⁴ F. Nathan, M. S. Rudner, N. H. Lindner, E. Berg, and G. Refael, arXiv:1610.03590 (2016).

⁵ J. C. W. Song and M. S. Rudner, PNAS **113**, 4658 (2016).

⁶ N. H. Lindner, E. Berg, and M. S. Rudner, arXiv:1603.03053 (2016).