Nonequilibrium phases of matter: An introduction and recent developments

Kazuaki Takasan[1,2]

[1]Department of Physics, University of California, Berkeley, [2]Material Science Division, Lawrence Berkeley National Laboratory

In the past decade, the development of experimental techniques has made it possible to realize and observe nonequilibrium states in many-body quantum systems, including solid-state systems and atomic-molecular-optical (AMO) systems. Theoretical researches have also been stimulated by this development and nonequilibrium quantum phenomena have become an important research subject in condensed matter physics in recent years. Using such nonequilibrium phenomena, it has become possible to realize quantum phases far away from equilibrium as steady or metastable states. Here, we call such states *nonequilibrium phases of matter*. They are not contained in the equilibrium phase diagram and are considered to be a new frontier, where exotic phases difficult to be realized in equilibrium (e.g., room temperature superconductivity) can be realized. In this lecture, I will start with an overview of the nonequilibrium phases of matter. I will present the background of the developments and what kinds of phases have been gathering interests in recent years.

Then, among the nonequilibrium phases of matter, I will focus on *Floquet systems* and *non-Hermitian systems* in this lecture. In Floquet (periodically driven) systems, the approach called Floquet engineering has been proposed to realize the desired quantum state by choosing an external drive and has been actively studied both theoretically and experimentally [1]. In particular, related experiments in solids driven by strong laser light are still challenging and gathering great attention recently [2]. In this lecture, I will explain the idea of the Floquet engineering for photoinduced phase transitions in solids, and then introduce several basic theoretical examples and corresponding experiments. If time allows, I will explain our works in this direction [3]. Non-Hermitian systems have attracted renewed attention in recent years thanks to the developments in the AMO experiments [4]. Since the recent developments are too rapid to be covered in this lecture, I will focus on asymmetric hopping models, which is the simplest example of the non-Hermitian topological phases [5]. Also, I will explain the related projects, where we introduced a model similar to the asymmetric hopping model and showed that the model can be regarded as a quantum analog of active matter [6].

[1] T. Oka and S. Kitamura, Annu. Rev. Condens. Mat. Phys. **10**, 387-408 (2019).

[2] J. W. McIver, *et al.*, Nat. Phys. **16**, 38–41 (2020).

[3] **KT**, A. Daido, N. Kawakami, Y. Yanase, Phys. Rev. B **95**, 134508 (2017).

[4] Y. Ashida, Z. Gong, M. Ueda, Adv. Phys. **69**, 3 (2020).

[5] Z. Gong, Y. Ashida, K. Kawabata, **KT**, S. Higashikawa, M. Ueda, Phys. Rev. X **8**, 031079 (2018).

[6] K. Adachi, **KT**, K. Kawaguchi, arXiv:2008.00996.