論文の内容の要旨

Floquet engineering of topological phenomena and nonlinear systems
(トポロジカル現象と非線形系のフロケエンジニアリング)

氏名　東川　翔

Periodically driven systems have a long history of study in many subfields of physics and periodic drives have long served as flexible experimental tools for controlling and even engineering non-equilibrium systems. Owing to the rapid development in laser and ultrafast spectroscopy techniques, this form of engineering of quantum systems, which is usually termed as Floquet engineering, has become an emergent field of research over the last decade. Exotic states of matter, that are not accessible in equilibrium systems, have been realized by means of Floquet engineering. In this thesis, we consider two applications of Floquet engineering to topological quantum phenomena and nonlinear classical systems.

In the first part of the study, we consider topological band structures in periodically driven systems. A Weyl fermion, which is a prototypical example of topological semimetals, has recently attracted considerable interest owing to its exotic magnetic response, namely the chiral magnetic effect. However, this response vanishes in a static lattice system such as a solid because Weyl fermions should appear in pairs within a single band because of the Nielsen-Ninomiya theorem. Here, we present a concrete model on a periodically driven three-dimensional lattice that features a single Weyl fermion within a single band, thereby surpassing the above limitation. The key idea is to utilize the nontrivial topology in the Floquet unitary operator, namely the periodicity of quasienergies. Its nontrivial topology ensures the presence and the stability of a single Weyl fermion in its quasienergy spectrum. Because of the emergent single Weyl fermion in the Floquet unitary operator, a spin-polarized gas moves parallel to its spin polarization under the external drive, which is a consequence of the spin-momentum locking of a Weyl fermion. Moreover, when we apply a magnetic field, a current flows antiparallel to the magnetic field and this current takes a quantized value for suitable band filling and temperature, which is a Floquet realization of the chiral magnetic effect. By generalizing the above idea to include symmetries, we give a topological classification of Floquet unitary operators in the Altland-Zirnbauer symmetry classes for all dimensionalities and construct concrete models with nontrivial topological numbers for each class and dimensionality. From these results, we show that all gapless surface states of topological insulators and superconductors can emerge in bulk quasienergy spectra in Floquet systems.

In the second part of the study, we consider periodically driven nonlinear systems governed by nonlinear stochastic equations. In periodically driven quantum systems, it is known that their dynamics is, on average, described by a static effective Hamiltonian according to the Floquet theorem and that the effective Hamiltonian is systematically determined from the high-frequency expansion. However, we cannot directly apply this theorem and the high-frequency expansion to nonlinear classical systems because they can be applied only to linear equations like the Schrödinger equation. Here, we overcome this difficulty by employing a master-equation approach and thereby develop the high-frequency expansion of their equations of motion. Our formalism is applicable not only to classical systems but also to quantum ones in symmetry-broken phases and covers both isolated and open systems. By analytically evaluating the higher-order terms of the high-frequency expansion, we find that an effective equation of motion derived from the high-frequency expansion well describes the exact time evolution for a high-frequency drive. In particular, for driven dissipative systems, it well reproduces the exact dynamics until they reach their non-equilibrium steady states. This result is in stark contrast to driven isolated systems, where the high-frequency expansion works only in the intermediate regime before they heat up to infinite-temperature states. These analytical findings are numerically confirmed for a single-body system and a many-body system by examples of the Kapitza pendulum with friction and a laser-driven magnet coupled with a thermal bath, respectively. Finally, we present an application to spintronics, where we demonstrate an optical control of a spin chirality by a laser.