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Article / Book Information

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論 文 要 旨

THESIS SUMMARY

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要旨（英文 800 語程度）
Thesis Summary（approx.800 English Words ）

Topological materials, characterized by their intrinsic topological invariants, exhibit intriguing response properties. While theoretical studies employing model computations have successfully elucidated the response behavior of individual topological materials, a comprehensive and universal understanding of these properties remains elusive. To address this gap, we aim to explore and establish universal response properties of topological materials through the framework of the effective field theory. The effective field theory provides a powerful approach to simplifying complex many-body problems by focusing only on the relevant degrees of freedom at a suitable energy scale. Its principal advantage lies in its ability to capture universal characteristics that transcend the details of the materials. In this thesis, we examine the universal response properties of the quantum Hall systems and the Weyl semimetals as two prominent classes of topological materials. The quantum Hall system is a relatively simple example of a topological material. Despite its seemingly straightforward setup, it exhibits a variety of Hall responses, including the Hall viscosity. Although numerous studies have explored individual quantum Hall states, a comprehensive and unified framework remains elusive. On the other hand, the Weyl semimetals offer an excellent platform for realizing relativistic physics in the context of condensed matter systems since the low-energy physics of the Weyl semimetals is governed by massless electrons. In particular, the axial anomaly emerges and gives rise to intriguing response behaviors. Investigating these responses is valuable not only for enhancing our understanding of the Weyl semimetals but also for deepening insights into other massless electronic systems, such as the neutron stars, the quark-gluon plasmas, and so on.

In the first part of the thesis, we explore the quantum Hall systems with Galilean invariance. To investigate all responses, including energy and momentum currents, we introduce external fields conjugate to these currents by placing the system on a non-relativistic curved spacetime, described by the Newton-Cartan geometry. This spacetime features three metrics corresponding to external fields conjugate to energy current, momentum density, and stress tensor. Electrons on a Newton-Cartan spacetime exhibit Milne symmetry in addition to the symmetries under U(1) gauge and general coordinate transformations. We construct the effective action based on these symmetries, imposing Milne invariance by dressing the external fields. Using a power counting scheme where the electromagnetic fields are of order of unity, we investigate nonlinear responses. The resulting action, up to next-to-next-to-leading order in the derivative expansion, includes four terms, such as the dressed Chern-Simons and Wen-Zee terms. From this, we compute the local currents induced by electromagnetic fields and identify the coefficients of these terms as the Hall conductivity, Hall viscosity, energy density, and energy magnetization. The dressing of external fields leads to universal relations between responses, with two key results: one shows the Hall conductivity determining the longitudinal conductivity at nonzero frequency, while the other shows the Hall viscosity contributing to nonlinear electrothermal conductivity at nonzero wave number.

In the second part of the thesis, we examine the Weyl semimetals using the low-energy effective field theory of massless Dirac fermions coupled to an axial gauge field, which

describes the separation of the Weyl nodes. We compute the charge current density in linear order in both vector and axial gauge fields. Regularization via the Pauli-Villars method, introducing a ghost field with infinite mass, allows for the proper definition of superficially divergent integrals. The resulting current density contains terms dependent on temperature and chemical potential as well as terms independent of these variables. The latter is just the Chern-Simons current, whose correct form is obtained owing to the regularization. In the static limit, the chiral magnetic current vanishes, which is consistent with the vanishing of the chiral magnetic effect in equilibrium. In the uniform limit, a dynamical chiral magnetic current emerges, with a coefficient 2/3 smaller in magnitude and opposite in sign compared to the chiral magnetic current. We further investigate the current density driven by a uniform but time-dependent magnetic field. Our analysis shows that the total transported charge is independent of both temperature and chemical potential. Additionally, we find that a pulsed magnetic field gives rise to a temporal Friedel oscillation, whose amplitude is determined by the temperature and the chemical potential.

Lastly, we compute the electromagnetic linear responses of the Weyl semimetals using chiral kinetic theory under the relaxation time approximation that ensures local charge conservation. The resulting current density, including the Chern-Simons current, agrees with the result of the low-energy field theory in the long wavelength and low frequency limit. We couple the current density with Maxwell's equation to investigate the dispersion relation of collective excitations. At the linear order in wave vector, the dispersion relation is determined by the anomalous Hall, chiral magnetic, and Ohmic conductivities. Importantly, one dispersion relation exhibits a positive imaginary part, suggesting exponential growing modes akin to the chiral plasma instability, with propagation oriented along or opposite to the direction of the Weyl node separation.