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Heat Transport as Torsional Responses and Keldysh Formalism in a Curved Spacetime

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Heat transport phenomena are of scientific and technological importance. Especially the thermal Hall effect is an interesting phenomenon in which the heat current flows perpendicular to a temperature gradient. Recent experiments revealed the effects of inelastic scattering on the anomalous Hall effect in ferromagnetic metals [1] and detected the magnon Hall effect in a ferromagnetic insulator [2]. A systematic framework for calculating the thermal Hall conductivity (THC) is highly desired.

Theoretically, the Kubo formula for the thermal conductivity is well established by introducing a gravitational potential [3], while that for the THC alone is not sufficient and should be augmented with the heat magnetization (HM) [4, 5]. Previous theories are unsatisfactory; it remains unclear how the scaling assumptions on the charge and heat currents are justified and furthermore how the theories are practically applied to disordered or interacting systems.

In this talk, we revisit the basics of heat transport from the gauge-theoretical viewpoint [6]. We begin with the Noether theorem and gauge principle and explain why a theory of heat transport involves gravity. A vielbein is a gauge field of gravity which is coupled to the energy current and induces a field strength called torsion. A torsional electric field is equivalent to a temperature gradient, and a torsional magnetic field is conjugate to the HM. Such a gauge-theoretical discussion yields the natural definition of the HM.

We also develop the Keldysh formalism in a curved spacetime to calculate these gravitational responses [6]. This is a natural extension of the gauge-covariant Keldysh formalism [7] by taking into account gauge fields of gravity. We derive the Green-function formulas for the Kubo-formula contribution and the HM applicable to disordered or interacting systems. In the clean and non-interacting limit, we reproduce the Berry-phase formula for the THC which satisfies the Wiedemann-Franz law [5].

References

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