Nonlinear Photocurrent in Topological Materials

Habib Rostami
Department of Physics, University of Bath, Claverton Down, Bath BA2 7AY, United Kingdom
hr745@bath.ac.uk

Abstract: Nonlinear transport phenomena, including charge and spin photogalvanic effects, are currently of great interest [1] due to their significance in both fundamental research and practical applications. Understanding these nonlinear responses relies on higher-order correlation functions, which reveal quantum geometry, topology, and many-body properties beyond the scope of linear response theory. Investigating higher-order correlations is vital for a comprehensive understanding of nonlinear transport in various materials and systems.

I will present our theoretical studies exploring light-induced nonlinear transport in charge, spin, and thermal (thermoelectric) channels in topological quantum materials, such as the quantum spin Hall system WTe_2 and the topological insulators as Bi_2Te_3. Our method is based on semiclassical Boltzmann transport, and full quantum theory using nonlinear Kubo's formalism and Feynman diagrams. We employ effective Hamiltonian to consider the electronic dispersion and topological character.

Our predictions [2] include an inter-band resonance enhancement in the Berry curvature dipole, derived from the momentum derivative the Berry curvature, describing the second-order Hall effect [2]. The tilted dispersion in the low-energy Hamiltonian transforms the typical interband resonance peak into a non-Lorentzian shape in the collision-less regime. We discuss the implications of these findings for understanding nonlinear Hall effects in WTe_2 and their relevance for probing quantum criticality of tilted Dirac fermion system. Furthermore, we investigate second- and third order rectified nonlinear spin currents [3] using single-color and two-colour laser beams in WTe_2. Our comprehensive analysis of the impact of a displacement field (U), light intensity, and polarization direction on nonlinear spin Hall current reveals the presence of an in-gap third-order spin current activated when the light frequency falls within the electronic bandgap. This discovery extends our understanding of in-gap (or sub-gap) photocurrents [4] in the spin channel, elucidating third order responses beyond previously discussed second order in-gap charge photocurrents. These findings offer insights into the intricate interplay between light and spin in materials, opening avenues for exploring and manipulating spin-related nonlinear phenomena in future THz applications, while maintaining time reversal symmetry.

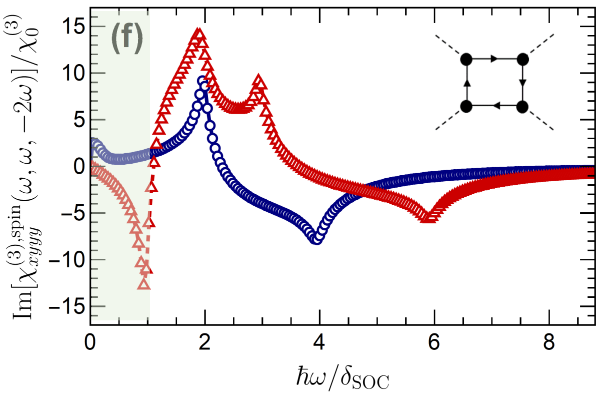

*Figure 1. Third-order spin Hall response as a function of the normalized incident energy and normalized out-of-plane gate potential (*blue: *$U = \delta_{soc}$ and red: $U = 2\delta_{soc}$) with respect to the spin–orbit coupling gap δ_{soc}. The inset shows a Feynman diagram that gives the dominant contribution to the in-gap nonlinear spin current.*

In 2D Fermi liquids, odd-parity Fermi surface deformations [5] exhibit anomalously slow relaxation rates, suppressed as $\tau_{\mathrm{AN}}^{-1} \sim T^4$ with temperature T, a departure from the standard Fermi-liquid $\tau_{\mathrm{FL}}^{-1} \sim T^2$ scaling. I will highlight our recent study [6] that illustrates that these enduring modes, often concealed in linear response, which can have a notable influence on nonlinear transport. We establish a direct relationship between the light-induced nonlinear thermoelectric currents and the remarkably prolonged relaxation time. These currents manifest in topological time-reversal invariant Fermi liquids, characterized by novel topological heat capacitance terms obtained by the thermal derivative of Berry curvature norm square average $C_\Omega = \partial_T \langle \Omega^2 \rangle$ that we call it as the *Berry curvature capacity* and similarly the *velocity-curvature capacity* $C_{\mathrm{v}} = \partial_T \langle v\Omega \rangle$. We quantify this phenomenon in topological insulators such as bismuth telluride Bi_2Te_3 which is an efficient thermoelectric material as well as a topological insulator with a hexagonal symmetric Fermi surface at the boundary of the system. We predict a non-monotonic dependence of the transverse and longitudinal light-induced thermoelectric effects, which could serve as a promising feature for experimental testing.

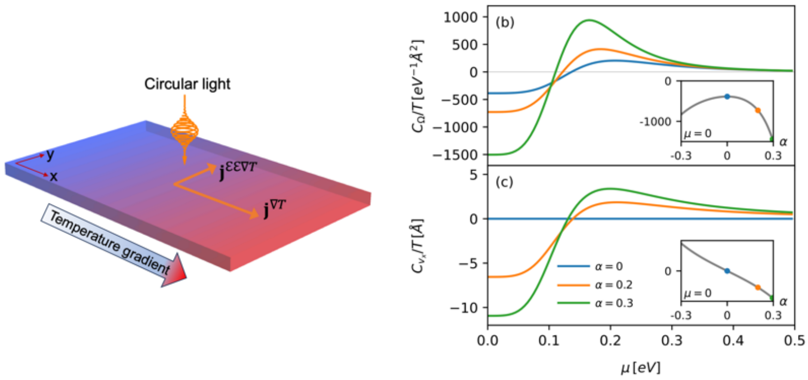

Figure 2. Light-induced nonlinear thermoelectric effect. We predict characteristic dependence of topological heat capacitance terms on the chemical potential (μ) and strain parameter (α).

Acknowledgment: I would like to express my gratitude to my co-authors V. Juričić, P. Bhalla, and J. Hofmann.

References:

[1] Q. Ma, R. K. Kumar, S.-Y. Xu, F. H. L. Koppens, and J. C. W. Song, Nat Rev Phys 5, 170 (2023).
[2] H. Rostami and V. Juričić, Physical Review Research 2, 013069 (2020).
[3] P. Bhalla and H. Rostami, New Journal of Physics 26, 023042 (2024).
[4] D. Kaplan, T. Holder, and B. Yan, Phys. Rev. Lett. 125, 227401 (2020).
[5] P. Ledwith, H. Guo, A. Shytov, and L. Levitov, Phys. Rev. Lett. 123, 116601 (2019).
[6] J. Hofmann and H. Rostami, arXiv:2312.12520.