Future plans: Directions of research into topology and light-matter interactions

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An exhilarating new line of research in our department is the experimental study of light-matter interactions. In August 2020, we established a new team, led by Dr. Fabian Menges, to advance our understanding of the fundamental electromagnetic properties and functionalities of material systems with quantum phases and topological surface states.

Light-matter interactions provide fascinating ways to study and control the quantum properties of solids and electromagnetic fields. They afford spectroscopic insights into several characteristic properties – such as the band dispersion and Berry curvature [1–3] – and can be leveraged to dynamically control materials based on a plethora of mechanisms, including Floquet effects, coherent phonon, and photoelectronic excitations. The coupling between photons and topological, fermionic quasi-particles is a particularly blossoming field of research, as it opens up new avenues to:

- engineer the physical properties of solids down to ultra-fast timescales,
- generate non-classical states of light, and
- harvest non-equilibrium effects that could prove useful for application in novel optoelectronic devices, light sources, detectors, and solar cells [4, 5].

We have identified numerous topological chiral crystals that can exhibit alluring optical properties [6] such as the circular photogalvanic effect (CPGE), a second-order optical response associated with photocurrents induced by circularly polarized light [7–11]. While the CPGE can also arise in non-topological materials, it may show unique features of topological origin, such as current quantization. Together with our collaborators, we have found significant evidence to suggest that photocurrents in the multifermion compound RhSi, although non-quantized, indeed display topological characteristics under mid-IR illumination [8]. The possibility of quantization of injection currents in monosilicides [10, 11] such as RhSi or CoSi appears to be hidden by very short hot-electron momentum-relaxation times (in the order of a few fs), indicating that the synthesis of chiral semimetals with smaller spin-orbit coupling may offer a promising route towards the development of more efficient infrared detectors.

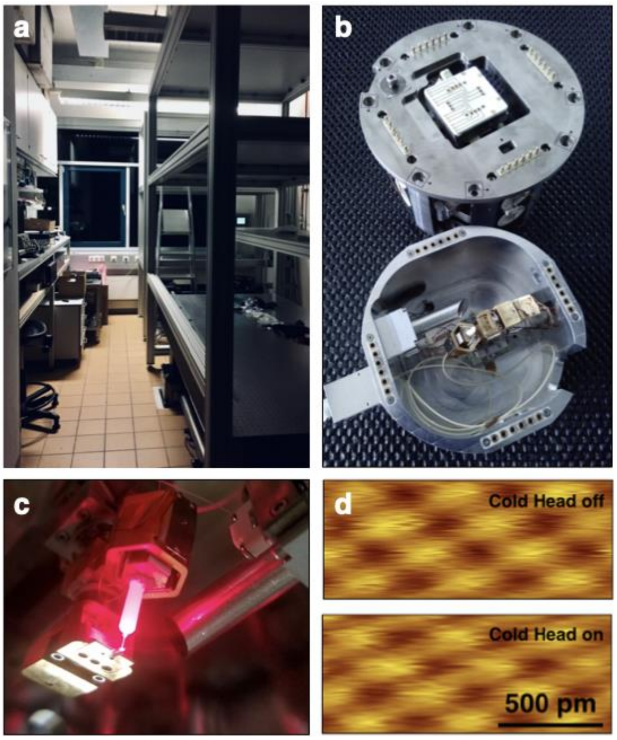

Fig. 1: a) The newly established 'Light-Matter Laboratory' that houses custom-built instruments for magneto-optical spectroscopy and b) photoinduced force microscopy. c) Image of cantilever-based optical near-field microscopy module with fiber interferometric read-out. d) Preliminary data illustrating STM imaging with atomic-spatial resolution on pyrolytic graphite.

To facilitate the discovery of new material functions between photo-excited topological fermions and their ultra-fast thermodynamic responses, we have now established our own experimental 'Light-Matter Laboratory', which houses two new custom-built instruments with several unique features and capabilities – a magneto-optical microscope with multiple scanning-probe inserts for near-field spectroscopy and a cryogenic, photo-thermal force microscope. Both instruments were developed in-house, in collaboration with two companies (Quantum Design, Renaissance Scientific). They have been designed to offer new insights into the electromagnetic response of matter in parameter regimes that have hitherto largely remained experimentally unexplored. The magneto-optical setup has a conical, superconducting, split-coil magnet for versatile optical access to the sample region (eight optical ports, up to 0.7 NA), a magnetic-field range of ±7 T, and a variable temperature range of 1.7–350 K. The scanning-probe microscope inserts are designed for optical near-field spectroscopy by means of photo-induced forces [12], scanning thermal microscopy [13], and plasmon-driven, scanning tunneling microscopy. These microscopes can all be coupled with state-of-the-art light sources, including an ultrafast Ti:Sapphire laser (Coherent Chameleon), a HeNe laser, an Argon laser, and multiple laser diodes operating in the visible/NIR spectrum of radiation. In addition, we will also invest in a tunable mid-IR quantum cascade laser to access low-energy excitations (down to 23 THz) in topological semimetals and insulators.

Near-term goals of our newly-formed research team include the spatio-spectral mapping of non-local conductivity in quantum Hall conductors via magneto-optical laser-scanning microscopy, as well as the real-space imaging of non-trivial photogalvanic and photothermoelectric effects. Other intriguing avenues of research we plan to explore include the development of new spectroscopic tools to directly probe the thermodynamic limits of topological quantum phases, mixed domain states, and polaritonic surface modes, via the photo-modulation of surface dispersion forces and thermal near-fields [14].

Our long-term goals include the study of polaritonic solid-state structures with electromagnetic topological orders emerging from the combined interplay of both bosonic and fermionic quantum statistics. There is, thus, a clear perspective to extend our ongoing efforts on crystal synthesis and the theoretical understanding of ‘photon-dressed’ matter, whose properties and functions are no longer exclusively embedded in its intrinsic chemical structure, but in the intricate details of electromagnetic reservoir couplings, dissipative driving, and thermalization dynamics.

More details on our plans will be presented during the Scientific Advisory Board site visit.

External Cooperation Partners

Adolfo Grushin (Insitute Neel CNRS); Martin Dressel (University of Stuttgart); Joseph Orenstein (UC Berkeley).

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