Thermal transport in topological semimetals

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Topological materials have been essential in discovering analogues of fermionic elementary particles and to test fundamental laws predicted in high-energy physics. Considering the richness of the physics that electrical transport in topological bulk materials has recently provided, our group seeks to unravel thermal transport signatures of new emergent quantum phenomena in topological semimetals. Within the last three years, we have designed and built high-resolution thermal transport measurement equipment with a sub- mK temperature resolution for bulk-, nano-, and micro-structures that can be operated in the temperature range from 1.8 to 400 K and in magnetic fields up to 9 T. Using this equipment, we have observed signatures of mixed axial-gravitational anomaly in the Weyl semimetal NbP, of hydrodynamic electron flow at the Planckian bound of dissipation in WP_2, and of the electron-phonon fluid in $PtSn_4$. Our research was highlighted in, among others, 'Nature News and Views' and in the 'New York Times'.

Inspired by the wide-spread detection of novel types of quasi-particles like the Weyl and Majorana fermions as well as by the observation of exotic quantum effects such as chiral anomalies in electrical transport experiments on topological materials, a new effort in thermal transport experiments has been started at the Max Planck Institute for Chemical Physics of Solids in 2015. Having established new collaborations with Harvard University, Stanford University, Berkley, IBM Research Zurich, and the Technische Universität Dresden, the first results of these efforts are reported in here.

Experimental signatures of the mixed-axial gravitational anomaly in the Weyl semimetal NbP

Conservation laws such as of charge, energy, and momentum play a central role in physics. In some special cases, however, classical conservation laws are broken at the quantum level by quantum fluctuations, in which case the theory is said to have quantum anomalies. One of the most prominent examples is the chiral anomaly, involving massless chiral fermions. These particles have their spin, or internal angular momentum, aligned either parallel or antiparallel with their linear momentum, labelled as left and right chirality, respectively. In three spatial dimensions, the chiral anomaly is the breakdown of the classical conservation law that dictates that the numbers of massless fermions of each chirality are separately conserved. This breakdown occurs in parallel ($\boldsymbol{E} \,||\, \boldsymbol{B}$) electric $\boldsymbol{E}$ and magnetic fields $\boldsymbol{B}$ (Fig. 1) and has been first observed in high-energy experiments. In addition, an underlying curved spacetime is predicted to provide a distinct contribution to a chiral imbalance, an effect known as the mixed axial-gravitational anomaly, which remains experimentally elusive. In a three-year-long project, an international team of physicists, material scientists, and string theoreticians around the Max Planck Institute for Chemical Physics of Solids have eventually observed this phenomenon in 2017 on Earth in a magneto-thermal transport experiment on the Weyl semimetal NbP. The mixed axial-gravitational anomaly was previously thought to only

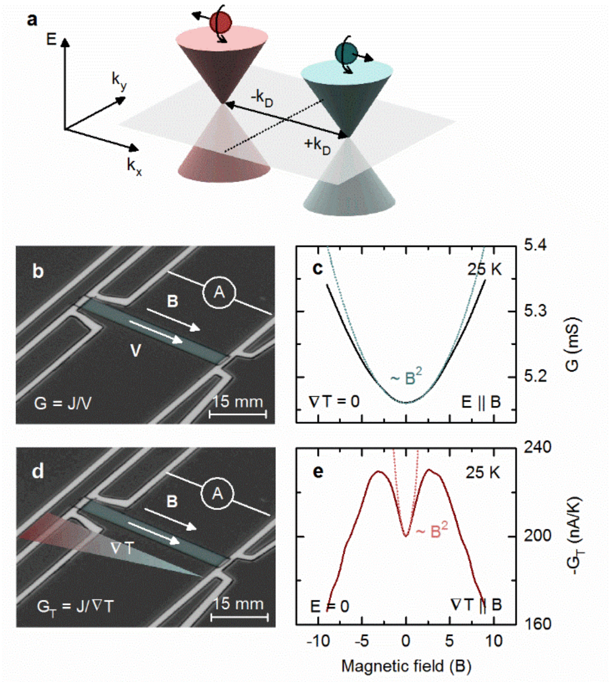

Fig.-1: Chiral and mixed axial-gravitational anomaly in the Weyl semimetal NbP. (a) Sketch of two Weyl cones with distinct chiralities $+\chi$ and $-\chi$, represented in green and red, respectively. The two chiral nodes are separated by $2k_D$ in momentum space. ***(b)*** *False-coloured optical micrograph of the measurement device used to measure the electrical conductance and to measure the magneto-thermoelectric conductance (d) Longitudinal G(**E** || **B**) and (e) G_T(**∇T** || **B**) as a function of the magnetic field **B** at a base temperature of 25 K (solid lines). [3]*

occur in extreme gravitational fields. Using the recently discovered Weyl semimetal NbP, the team mimicked a gravitational field in their test sample by imposing a temperature gradient $\nabla \boldsymbol{T}$. The experimental signature of the mixed axial-gravitational anomaly is a positive magneto-thermoelectric conductance G_T in a parallel temperature gradient and a magnetic field ($\nabla \boldsymbol{T} \parallel \boldsymbol{B}$) (Fig. 1(e)).

This result could lead to a more evidence-based model for the understanding the universe and for improving the energy-conversion process in electronic devices. The research was highlighted in, among others, ‘Nature News and Views’ and in the ‘New York Times’.

Electrical and thermal transport at the Planckian bound of dissipation in the hydrodynamic electron fluid WP_2

In an overwhelmingly large group of conducting materials, charge transport can be described by the rather simple model of a free-electron gas. The base of this model is that the carriers move unimpededly until they scatter on phonons or defects. Such collisions relax both momentum and energy currents and consequently impose a resistance to charge and heat flow alike. In most conventional conductors, electrical and thermal transport are therefore related *via* the Wiedemann–Franz law, which states that the product of the electrical resistivity and the thermal conductivity divided by the temperature is a constant. The conventional free-electron model, however, fails to describe transport in interacting electron systems. Recently, it has been suggested that the theory of hydrodynamics, which is normally applied to explain the behaviour of classical liquids like water, could be employed to describe the collective motion of electrons in such a system.

In 2017, our team has found signatures of hydrodynamic electron flow in the Weyl-semimetal tungsten phosphide (WP_2). Using thermal and magneto-electric transport experiments, the transition from a conventional metallic state at higher temperatures to a hydrodynamic electron fluid below 20 K has been observed. The hydrodynamic regime is characterized by a viscosity-induced dependence of the electrical resistivity on the square of the channel width and by the observation of a strong violation of the Wiedemann-Franz law (Fig. 2). As the strong violation of the Wiedemann Franz law created much excitement in the solid-state community, it was recently independently confirmed by collaborators in Paris.

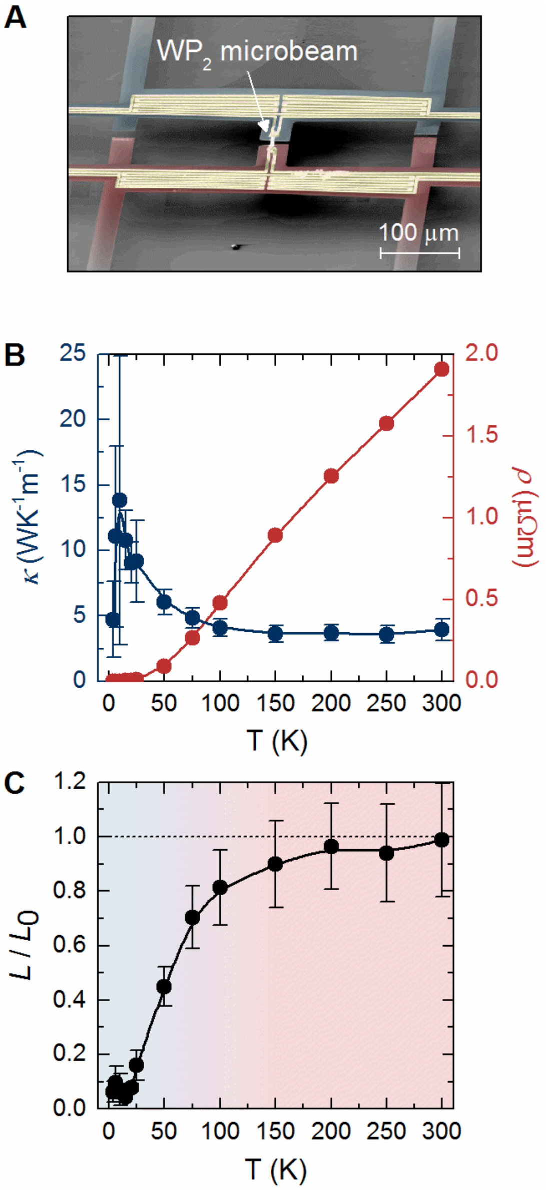

*Fig.-2: Violation of the Wiedemann–Franz law. (a) False-coloured SEM image of a microdevice for measuring thermal transport that consists of two suspended platforms that are bridged by a 2.5 μm-wide WP_2 ribbon. (**b**) Thermal conductivity κ (left axis) and electrical resistivity ρ (right axis) of the micro-ribbon as a function of temperature. (**c**) Lorenz number $L = \kappa T \rho$, calculated from the data in (b). [6]*

The relaxation times for momentum and energy dissipating processes are extracted from magneto-hydrodynamic experiments and complementary Hall measurements. Following the uncertainty principle, both are limited by the Planckian bound of dissipation, independent of the underlying transport regime. This is remarkable, as it turns out that the electron system generates entropy in a very simple and universal way, in which the only relevant scale is the temperature.

Thermoelectric signatures of the electron-phonon fluid in $PtSn_4$

Conventional transport in condensed matter systems relies on the existence two species of quasi-particles, electrons and phonons. Heat is carried by both electrons and phonons, while charge is only transported by electrons. The charge current can only be relaxed by processes that relax the total momentum of the electrons. The simplest example is electron- impurity scattering, which instantly relaxes momentum to the environment. The case of electron-phonon scattering is more subtle: in this case, the electron momentum is transferred to the phonons and could be transferred back to the electrons at a later scattering event. This kind of process is usually negligible, because phonons quickly relax momentum to the environment (e.g. *via* phonon-phonon Umklapp scattering), and therefore act effectively as a momentum sink.

Strong interactions between electrons and phonons, however, can lead to collective behaviour that conserves the total momentum, which in some special cases resembles that of viscous fluids. An electron-phonon fluid is expected to exhibit strong phonon-drag transport signatures and an anomalously low thermal conductivity. Employing electrical resistivity, Hall, thermopower, and thermal conductivity measurements on the Dirac semimetal $PtSn_4$, our team found a phonon-drag peak in the temperature-dependent thermopower near 14 K and the concurrent breakdown of the Lorenz ratio below the Sommerfeld value in 2017 (Fig. 3). This provides evidence for the presence of an electron-phonon fluid with quasi-conserved total momentum. A hierarchy between momentum-conserving and momentum-relaxing scattering time-scales is corroborated through measurements of the magnetic field dependence of the electrical and Hall resistivity and of the thermal conductivity. These results show that $PtSn_4$ exhibits key features of hydrodynamic transport, the electrical and Hall resistivity, and thermal conductivity. These results show that $PtSn_4$ exhibits key features of hydrodynamic transport.

Today, we focus on pushing the existing knowledge in fundamental physics by seeking purely thermal transport signatures of the gravitational anomaly, anomalous Nernst effects, and thermal Hall effects in magnetic and in non-magnetic Weyl systems. Further, we investigate strongly correlated topological matter, such as axion insulator phases. This is only enabled by the unique combination of expertise in materials research and thermal transport at the Max Planck Institute for Chemical Physics of Solids.

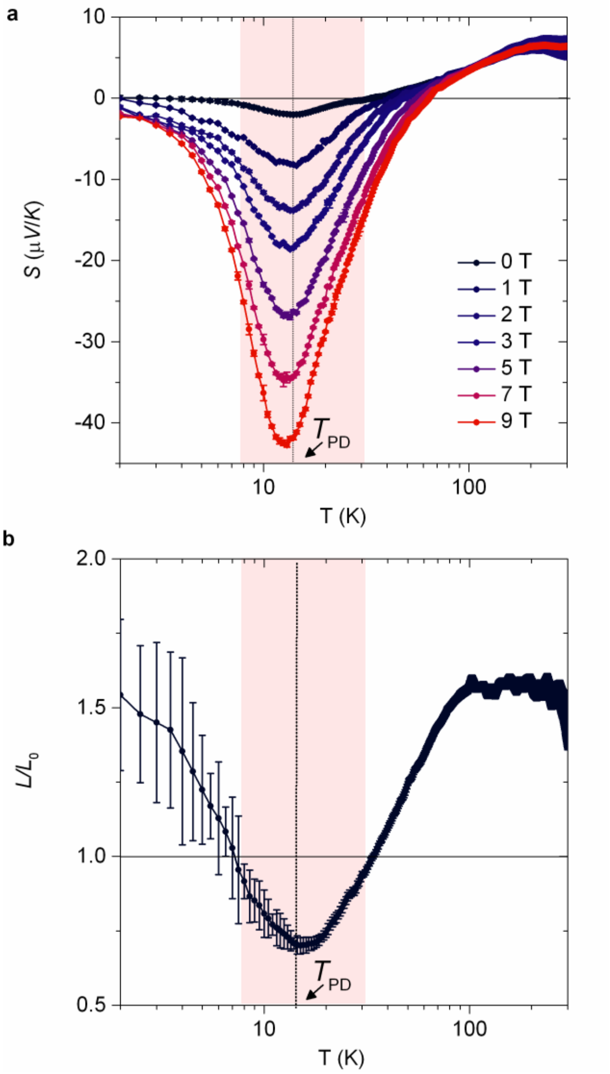

Fig.-3: Signatures of the electron-phonon fluid in $PtSn_4$. (a) The thermopower S as a function of temperature for various magnetic fields shows a phonon drag peak near T_{PD} = 14 K. (b) Lorenz number normalized by the Sommerfeld value L_0 shows a breakdown ($L < L_0$) around T_{PD} (marked by red-shaded area).

External Cooperation Partners

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