

## Non-Local Transport in Ultra-Pure Delafossites

Andrew Mackenzie<sup>#</sup>, Graham Baker<sup>##</sup>, Michal Moravec, Philippa McGuinness, Elina Zhakina and Seunghyun Khim

Over the past decade there has been considerable international excitement about the (re-)observation of hydrodynamic electronic flow, with experiments performed on doped semiconductors including graphene, and on metals. This has in turn led to careful examination of what one means by electron hydrodynamics, with initial claims softening over time as it becomes clear that what at first sight looked to be ‘smoking gun’ signatures of hydrodynamic flow can also have alternative explanations. As well as identifying new transport phenomena in our platform of choice, the delafossite metals, we have invested considerable effort in explaining how hydrodynamic transport fits into the broader spectrum of non-local transport effects, and hope to clear up some confusion that exists in the field.

The experimental side of our work has been two-fold. First, we have examined the phenomenon of ‘directional ballistics’ that we first identified in an electron focusing experiment in 2019 [1]. By cutting channels from one single crystal, oriented at different angles to the nearly hexagonal Fermi surface of PdCoO<sub>2</sub>, we showed that the directional effects can be substantial: up to a factor of three change of the d.c. resistivity has been demonstrated so far [2, 3]. In complementary work on mesoscopic squares, we again highlighted directional effects both in zero field transport and magnetoresistance and Hall effect, and provided a ‘text-book’ example of Büttiker’s extension of the Onsager relations to non-local transport [4]. In this latter work we also explicitly studied the disorder dependence of

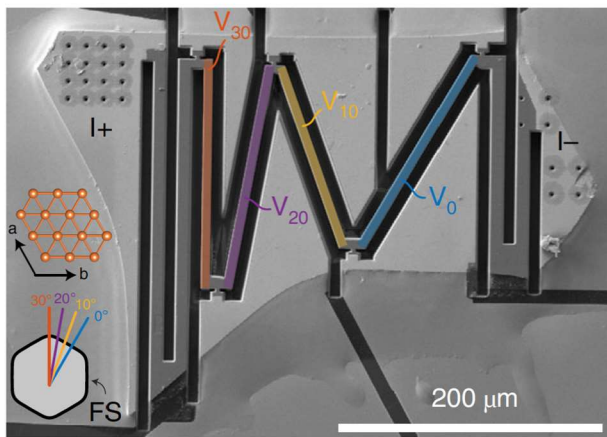


Fig. 1: The FIB-sculpted device used in an explicit demonstration of directional ballistic transport in PdCoO<sub>2</sub>. The four color-coded tracks range from the directions subject to most (30°) to least (0°) boundary scattering. The scattering is lowest for the 0° orientation because 1/3 of the quasiparticles first injected into the track, or emerging from bulk scattering events, are moving parallel to the walls. The effect is large, and would be banned by the lattice symmetry for ohmic transport [2].

the observed phenomena by sequentially irradiating our devices to introduce controlled levels of point defects, enabling a quantitative comparison of the effects of elastic and inelastic scattering on the transport properties [5].

The second substantial piece of experimental work, performed at the University of British Columbia in a bespoke microwave bolometer in the group of Doug Bonn, was a systematic study of the electrodynamics of PdCoO<sub>2</sub> [6]. The unique capabilities of this instrument enabled the first explicit demonstration of the correctness of decades old predictions of the frequency dependence of the skin effect (in Sr<sub>2</sub>RuO<sub>4</sub>) and anomalous skin effect (in Sn), followed by experiments showing that directional effects from the Fermi surface of PdCoO<sub>2</sub> alter not just the magnitude of the a.c. surface resistance but also its frequency dependence.

The frequency dependence of the signal from PdCoO<sub>2</sub> was a surprise. To understand it, one of us (Graham Baker) wrote a code to calculate the Boltzmann theory prediction of the electrodynamic response for a material of arbitrary Fermi surface topography. This not only explained the data from PdCoO<sub>2</sub> but also provides a

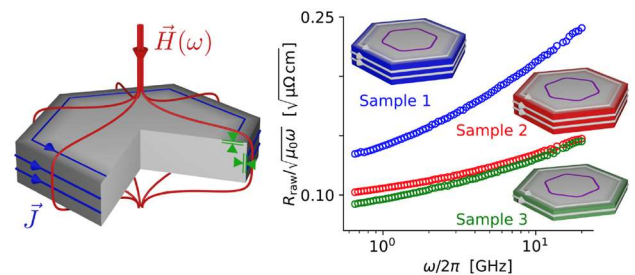


Fig. 2: Remarkably, directional ballistic effects, tuned by varying the skin depth in a broadband microwave experiment on PdCoO<sub>2</sub>, change not just the value but also the frequency dependence of the microwave conductivity.

highly didactic resource that allows the investigation of a full range of transport phenomena spanning the ohmic, ballistic and hydrodynamic regimes.

Ohmic transport is both local and well-understood, but the non-local ballistic and hydrodynamic regimes are far more subtle, and are strongly overlapping. This is the case in PdCoO<sub>2</sub>, in which simultaneous signatures of ballistic and viscous transport are observed [6]. It is also true in the other compounds that have been put forward as platforms for the study of electron hydrodynamics. One subtlety is that although viscosity naturally arises from electron-electron scattering or electron – phonon scattering in the presence of phonon drag, it can also be the result of small-angle impurity scattering, as shown by explicit calculations reported in References [6, 7]. Unfortunately, the literature remains rather confused on this most basic of points.

In an effort to share the insights gained in our studies of PdCoO<sub>2</sub>, and reduce the confusion in the field, we have written further papers on the theory of non-local transport [8, 9]. Reference [9], in particular, aims to provide a didactic perspective, explaining that while electron hydrodynamics is fascinating, it is only one particular sub-topic of the even more fascinating field of non-local electron transport, and should be seen in that context. We hope that the article will be of use to those entering this area of research in future.

### External Cooperation Partners

Doug Bonn (University of British Columbia, Vancouver, Canada); David Goldhaber-Gordon (Stanford University, US); Jörg Schmalian and Davide Valentis (Karlsruhe Institute of Technology, Germany); Roderich Moessner (Max Planck Institute for Physics of Complex Systems, Dresden, Germany); Philip Moll (Max Planck Institute for Structural Dynamics, Hamburg, Germany).

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#andy.mackenzie@cpfs.mpg.de

##graham.baker@cpfs.mpg.de