Electronic Hydrodynamics

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The quest to discover materials in which electron flow is influence by the laws of hydrodynamics rather than being fully ohmic is over fifty years old. Only now is the hydrodynamic regime becoming attainable in ultrapure materials. Here we describe our research on viscous electronic flow in the delafossite metals, describing our first measurements published in 2016 and the ways in which we are extending the study of hydrodynamic effects to include the application of external magnetic fields.

If a snapshot were taken of the flow velocity profile of an electron moving through a two-dimensional channel of a standard metal, it would look like the one shown in Fig. 1a. As the electrons flow, they scatter very frequently from lattice imperfections or phonons so that, on average, their flow velocity in the bulk of the channel is independent of y. There will be some extra scattering from the channel boundaries, but its effects will be seen only very close to those boun-daries, and make little difference to the overall flow resistance in all but the very narrowest wires. Because the scattering originates from features of the material through which the conduction electrons are flowing, the resistance is essentially entirely determined by the resistivity, which is a property of the material.

The mental picture represented by Fig. 1a is so strongly ingrained in the mind of a condensed matter physicist that the alternative limit, shown in Fig. 1b, has not been widely considered. Here, there is no scattering of the electrons from the host lattice or its excitations; the only scattering is between the elec-trons themselves. If the electrons only scatter from one other, they can exchange momentum but the overall momentum of the electron system is con-served. The only place that this is violated is at the boundary of the channel, so there is now a y dependence of the velocity, which is maximum at the centre. In these circumstances, the flow resistance is determined by details of the boundary scattering and how well the electrons can couple to the boun-daries i.e. a transverse coupling along the y direction. The quantity that parametrizes this coupling is the shear viscosity η, which is a property of the fluid, not of the medium through which it flows.

This simple discussion is an example of a more general principle, so-called hydrodynamic physics. If a fluid's flow is described by conserved quantities, there will be associated hydrodynamic modes and coefficients. Here, the conserved quantity in the bulk of the hydrodynamic electron fluid is its momentum; this conservation is associated with the coefficient η and the role that it plays in determining the flow resistance.

Although first considered theoretically over half a century ago [1], electron hydrodynamics has been very sparsely studied, for a simple reason. To approach the hydrodynamic limit, one needs a material in which the internal scattering rate from defects or excitations is very small. Almost every known metal fails to satisfy this demanding criterion, so electron hydrodynamics did not seem likely to be grounded in experimental reality, except in the most special of circumstances [2]. Over the past decade, however, considerable theoretical attention has been paid to the possibility that in some special materials in which the internal electronic scattering rate is particularly high [3], there might be a hierarchy of scattering rates leading to quasi-conservation of momentum and a contribution to the resistance from hydrodynamic effects [4]. Testing experimentally for hydrodynamic effects in such strongly scattering materials is a formidable challenge, but the renewed interest in electron hydrodynamics stimulates the search for materials in which the hydrodynamic regime may be attainable because of very low internal scattering rates with the appropriate hierarchy. Our strategy has been to look for such materials and use them to gain ex-perience in how to
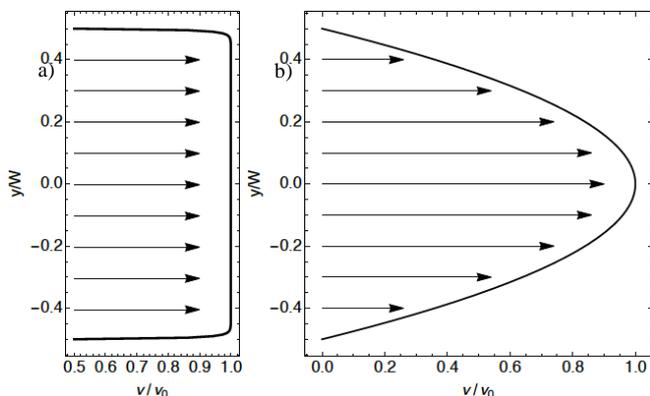

Fig.-1: Velocity profiles across a two-dimensional channel of width W for ohmic (a) and hydrodynamic (b) electron flow.

probe hydrodynamic effects. This is interesting in its own right, but also the first step in a programme in which we ultimately hope to extend study to the very strong-scattering systems.

The materials that have provided us with the platform on which to attempt our experiments are the metallic delafossites $PdCoO_2$ and $PtCoO_2$. These are remarkably simple, non-magnetic metals with only a single band crossing the Fermi level. We have performed in-depth transport, magnetic and spectroscopic studies of these compounds and their close relatives $PdRhO_2$ and $PdCrO_2$, and have developed a good knowledge of their bulk electronic structure [5-9]. One of the most remarkable features of $PdCoO_2$ and $PtCoO_2$ is their astonishing conductivity. At room temperature the electronic mean free path is longer than that of Ag, Au, Cu or Al, rising at low temperatures to tens of microns in $PdCoO_2$. This indicates that momentum-relaxing internal scattering is very weak, and there is also evidence for strong 'phonon drag' which not only suppresses momentum-relaxing electron-phonon scattering but converts this scattering into a potential source of the momentum-conserving processes vital for the observation of electron hydrodynamics.

Motivated by our knowledge of the remarkable properties of the delafossite metals, we embarked on a programme of crystal growth and microstructuring to
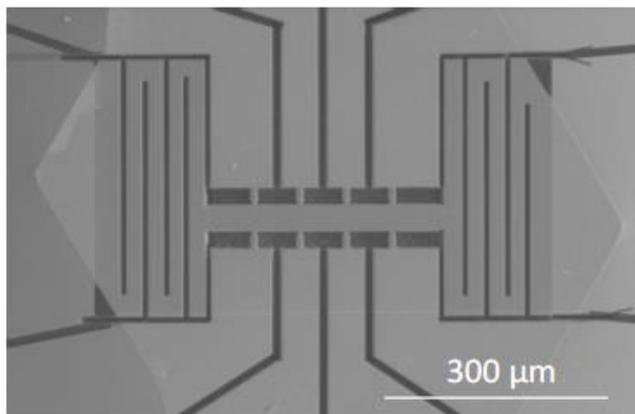
Fig.-2: A plate-like single crystal of PtCoO₂ (crystal edges visible with 120° vertices on left and right of photo) that has been sculpted using a focused ion beam to inject current, via long meanders, to an experimental channel with eight voltage probing electrical contacts. The sculpting steps can be multiply repeated to sequentially narrow the channel and look for viscous contributions to the resulting electrical flow resistance.

produce width-restricted conduction channels designed to reveal signatures of viscous flow that might be present. Thanks to modern techniques for focused ion beam sculpting the relevant structures can be fabricated with extremely high precision; an example is shown in Fig. 2. In our initial experiments on $PdCoO_2$ we concentrated on a com-parison of flow resistance in zero applied magnetic fields in samples of varying width and the results of kinetic theory calculations that are capable of tuning between fully ohmic and fully hydrodynamic regimes. Based on this comparison, we concluded that electronic viscosity strongly influences transport through restricted channels of $PdCoO_2$, and estimated the value of η to be approximately 0.1 m²/s [10]. Independent work on graphene by two other groups reached similar conclusions about electronic viscosity [11, 12], and the simultaneous publication of the three papers has led to an explosion of interest in electronic hydrodynamics.

Our strategy to advance the field is to work on 'magneto-electronic hydrodynamics' in which magnetic fields are combined with size-restricted devices to study viscous effects. The term 'magneto-hydrodynamics' is well known from plasma physics in which the relevant regime contains strongly non-linear physics. In contrast, we work at fields that are sufficiently small that the problem remains linear, though far from trivial. In fact, until very recently there was no kinetic theory in applied magnetic fields with which experiments could be compared. We set out to address this by establishing a collaboration with theorists Thomas Scaffidi and Joel Moore from UC Berkeley, laying the foundations for the relevant theory [13]. That showed that the relevant experimental quantities are magnetoresistance and Hall effect data from samples of restricted geometry, normalized to the same quantities measured in bulk crystals. At time of writing (spring 2018) we are conducting an extensive programme of experiments to measure these quantities, starting with the magneto-transport of bulk crystals sculpted to well-defined geometries [14]. The next step will be the careful comparison of width-restricted data with the prediction of theory; the main challenge for the latter is to perform computationally intensive calculations for relatively wide channels in which ballistic and viscous effects can in principle be separated. Initial results (as yet unpublished) are highly promising, and suggest that viscous contributions are still resolvable when they are extremely small. It seems to be possible to observe small hydrodynamic contributions even in regimes of

temperature and channel width for which naïve estimates would have said that ohmic contributions would be so dominant that they would mask all hydrodynamic effects. This gives grounds for optimism that searches for hydrodynamic effects will be possible in future using magnetotransport not just in delafossites but in the still more exotic situations in which electron-electron scattering is extremely strong, for example in near quantum critical points [3]. The future seems bright for the experimental study of electronic hydrodynamics, something that could hardly have been imagined when the first theoretical discussions appeared in the 1960s.

External Cooperation Partners

Our experimental work on electronic hydrodynamics was done in-house but we collaborate quite intensively with the external theoretical groups of T. Scaffidi and J.E. Moore at UC Berkeley and S.A. Hartnoll at Stanford University, as well as with P. Surowka and R. Moessner from our neighbour Max Planck Institute for Complex Systems.

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