

## Quantum Hydrodynamic Transport in Graphene

*Transport in inhomogeneous quantum critical fluids and in the Dirac fluid in graphene*

Andrew Lucas, Jesse Crossno, Kin Chung Fong, Philip Kim, Subir Sachdev  
arXiv:1510.01738

*Observation of the Dirac fluid and the breakdown of the Wiedemann-Franz law in graphene*

Jesse Crossno, Jing K. Shi, Ke Wang, Xiaomeng Liu, Achim Harzheim, Andrew Lucas, Subir Sachdev, Philip Kim, Takashi Taniguchi, Kenji Watanabe, Thomas A. Ohki, Kin Chung Fong  
arXiv:1509.04713

*Negative local resistance due to viscous electron backflow in graphene*

D. A. Bandurin, I. Torre, R. Krishna Kumar, M. Ben Shalom, A. Tomadin, A. Principi, G. H. Auton, E. Khestanova, K. S. Novoselov, I. V. Grigorieva, L. A. Ponomarenko, A. K. Geim, M. Polini  
arXiv:1509.04165

*Electron Viscosity, Current Vortices and Negative Nonlocal Resistance in Graphene*

Leonid Levitov, Gregory Falkovich  
arXiv:1508.00836

*Non-local transport and the hydrodynamic shear viscosity in graphene*

Iacopo Torre, Andrea Tomadin, Andre K. Geim, Marco Polini  
arXiv:1508.00363

*Collision-dominated nonlinear hydrodynamics in graphene*

U. Briskot, M. Schütt, I. V. Gornyi, M. Titov, B. N. Narozhny, A. D. Mirlin  
arXiv:1507.08946

*Bulk and shear viscosities of the 2D electron liquid in a doped graphene sheet*

Alessandro Principi, Giovanni Vignale, Matteo Carrega, Marco Polini  
arXiv:1506.06030

**Recommended with a commentary by Francisco Guinea,  
Imdea Nanoscience and University of Manchester**

In recent months, a number of theoretical and experimental articles dealing with the electron fluid in graphene in the hydrodynamic regime have been posted in cond-mat.

Although condensed matter physicists speak of the electron fluid within a metal, the motion of electrons in a metal is quite different from those of molecules in an ordinary fluid, like water. The understanding of the electronic properties of solids require the use of quantum mechanics. Concepts such as hydrodynamic flow, or viscosity, have proven difficult to observe in the non degenerate electron liquid, although vortices and quantum turbulence in superfluids has been extensively studied for a long time[1, 2].

For hydrodynamics to apply, two requisites need to be valid: i) the existence of regions of dimensions much larger than the interparticle spacing where local equilibrium can be defined, and ii) the momentum in a given region must relax

solely through inter particle collisions. Scattering with defects should be negligible. In the electron liquid within a metal, electron-electron scattering and electron impurity elastic scattering are described by two times,  $\tau_{ee}$  and  $\tau_{elastic}$ , and, usually,  $\tau_{elastic} \ll \tau_{ee}$ . In most circumstances, electrons in a normal metal cannot reach the hydrodynamic regime. The local quasiparticle distribution is better described by the Boltzmann equation. Nevertheless, a solid theoretical background was been developed[3, 4], supported by few experiments in very clean 2D electron liquids[5].

The situation has changed with the advent of graphene. Elastic scattering can be minimized by encapsulating the samples with BN, and mean free paths of order of microns have been achieved. Moreover, the lightness of the carbon atoms makes in plane phonons highly energetic, so that electron-phonon scattering is negligible up to room temperature. The screening length of the electron liquid in graphene is much larger than in other 2D electron liquids, due to the low electronic density of states, making electron-electron interactions more important. A number of theoretical[6, 7, 8, 9] and experimental works[10, 11, 12] (note that[11, 12] include a significant amount of theoretical analysis) have been recently posted, addressing the possible existence of an electronic hydrodynamic regime in graphene.

References[6, 7, 9, 10] analyze graphene away from the neutrality point, where it behaves like an ordinary electron gas, although with a very long elastic mean free path. For the very clean samples studied in[10] electron-electron scattering dominates above liquid nitrogen temperatures. The existence of an hydrodynamic regime implies that vortices are formed when current is injected through narrow contacts. These vortices lead to electron flow in opposite direction to the injected current. As a result, voltages are induced away from the contacts. The measurements reported in[10] confirm the existence of voltages consistent with an hydrodynamic regime. As the temperature increases, the negative flow is reduced, as the electronic viscosity is lowered. The viscosity of the electron fluid,  $\nu_G \approx 0.1 \text{ m}^2\text{s}^{-1}$ , is much higher than that of other highly viscous fluids, such as honey ( $\nu_{honey} \approx 0.002 - 0.005 \text{ m}^2\text{s}^{-1}$ ).

References[11, 12] address the hydrodynamic regime in graphene near the neutrality point. When the Fermi energy coincides with the Dirac energy, interactions turn graphene into a critical system, that is, a system at the verge of a phase transition (between a metallic and an insulating phase). The critical regime leads to a non trivial dependence of many quantities on parameters such as temperature or applied fields. Refs.[11, 12] focus on the two main transport coefficients, the electrical and thermal conductivities. In a normal metal, these quantities are related by Wiedemann's law, due to the fact that carriers behave in the same manner under potential and thermal gradients. Graphene at the critical point is a massless fermion system, where electrons and holes coexist. Electrons and holes move in the same direction in a thermal gradient, while an electric field makes them move in opposite directions. Momentum conserving collisions between electrons and holes relax in different ways thermal and charge currents, leading to important deviations from Wiedemann's law.

It is finally interesting to note that another recent preprint addresses a topic

of great interest in quantum field theory, the Hall viscosity of a relativistic fluid[13]. This study refers to the Hall viscosity of the graphene lattice and other 2D and 3D systems with massless electrons.

## References

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