# Observing the Dirac-fluid regime at room temperature

**Alexander Block[1,2],**
Alessandro Principi[3], Niels C.H. Hesp[1], Aron W. Cummings[2], Matz Liebel[1], Kenji Watanabe[4], Takashi Taniguchi[5], Stephan Roche[2,6], Frank H. L. Koppens[1,6], Niek F. van Hulst[1,6], Klaas-Jan Tielrooij[2]
[1]ICFO, The Institute of Photonic Sciences, BIST, Castelldefels, Spain
[2]ICN2, Catalan Institute of Nanoscience and Nanotechnology, CSIC and BIST, Bellaterra, Spain
[3]School of Physics and Astronomy, University of Manchester, Manchester, UK
[4]Research Center for Functional Materials, National Institute for Materials Science, Tsukuba, Japan
[5]International Center for Materials Nanoarchitectonics, National Institute for Materials Science, Tsukuba, Japan
[6]ICREA, Institució Catalana de Recerca i Estudis Avançats, Barcelona, Spain
Alexander.Block@ICN2.cat

The electronic transport of heat and charge in solids at room temperature is typically understood in terms of diffusive and ballistic motion of point particles. However, early theoretical work suggested that the strong interaction between electrons could – under certain circumstances – lead to a viscous, fluid-like behavior. Only recently, with the advance of ultraclean 2D electron systems such as graphene, it has become feasible to experimentally access this notoriously difficult regime of electron hydrodynamics [1-11]. To date, hydrodynamic viscous transport has been observed via electrical device measurements [2-7] and scanning probe microscopy [8, 9]. However, these studies have typically been limited to cryogenic temperatures and ultraclean samples. Furthermore, an even more elusive manifestation of hydrodynamic behavior – the quantum-critical Dirac-fluid regime with enhanced thermal transport – has been observed indirectly as a violation of the Wiedemann-Franz law [10] and as a contribution to the Drude scattering rate [11].

Here [12], we present direct signatures of hydrodynamics, including the Dirac-fluid regime, at room temperature in standard quality graphene. We directly track the motion of optically excited electronic heat pulses in the temporal domain using a split-gate device via ultrafast thermoelectric microscopy. This novel technique allows us to quantify heat transport on the femtosecond-nanometer scale and at room temperature. By simultaneously controlling the electron temperature and the Fermi level, we are able to tune in and out of the Dirac-fluid regime of electron motion. We observe a thermal diffusivity of the Dirac fluid that is more than two orders of magnitude larger compared than in the non-interacting, diffusive regime, and it persists at room temperature, in agreement with transport calculations.

Besides the fundamental breakthrough, we believe that the surprisingly long-range thermal transport, as well as the possibility of switching the effect on and off, may lead to technological applications, e.g. in thermal management.

References

[1] M. Polini, A.K. Geim, *Physics Today* **73**, 6 (2020) pp. 28-34
[2] D.A. Baudurin, et al., *Science* **351** (2016) pp. 1055–1058
[3] P.J.W. Moll, et al., *Science*. **351** (2016) pp. 1061–1064
[4] R. Krishna Kumar, et al., *Nat. Phys.* **13** (2017) pp. 1182–1185
[5] B.A. Braem, *Phys. Rev. B.* **98** (2018) pp. 241304
[6] J. Gooth, et al., *Nat. Commun.* **9** (2018) pp. 4093
[7] Berdyugin, et al., *Science* **364** (2019) pp. 162–165
[8] J. A. Sulpizio, et al., *Nature* **576** (2019) pp. 75–79
[9] M.J.H. Ku, et al., *arXiv preprint* (2019) *arXiv:1905.10791*
[10] J. Crossno, et al., *Science* **351** (2016) pp. 1058–1061
[11] P. Gallagher, et al., *Science* **364** (2019) pp. 158–162
[12] A. Block et al., *submitted*