Imaging of work and dissipation in the quantum Hall state

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We developed a scanning nanoSQUID-on-tip that resides at the apex of a sharp pipette acting simultaneously as nanomagnetometer with single spin sensitivity and as nanothermometer providing cryogenic thermal imaging with four orders of magnitude improved thermal sensitivity of below 1 μK [1]. The non-contact non-invasive thermometry allows thermal imaging of minute energy dissipation down to the level of direct visualization and control of heat generated by electrons scattering off a single atomic defect in graphene [2]. Utilizing this tool we image and investigate dissipation mechanisms in the quantum Hall state in graphene, revealing that the dissipation is governed by crosstalk between counterpropagating downstream and upstream channels that appear at graphene boundaries because of edge reconstruction. Instead of local Joule heating, however, the dissipation mechanism comprises two distinct and spatially separated processes, which we resolve and image independently. The work generating process involves elastic tunneling of charge carriers between the quantum channels, which directly affects the transport properties but does not generate local heat. The heat and entropy generation process occurs nonlocally upon inelastic resonant scattering off single atomic defects at graphene edges. The findings offer insight into the mechanisms responsible for the breakdown of topological protection and suggest venues for engineering more robust quantum states.

[1] D. Halbertal, J. Cuppens, M. Ben Shalom, L. Embon, N. Shadmi, Y. Anahory, H. R. Naren, J. Sarkar, A. Uri, Y. Ronen, Y. Myasoedov, L. S. Levitov, E. Joselevich, A. K. Geim, and E. Zeldov, Nature **539**, 407 (2016).

[2] D. Halbertal, M. Ben Shalom, A. Uri, K. Bagani, A.Y. Meltzer, I. Marcus, Y. Myasoedov, J. Birkbeck, L.S. Levitov, A.K. Geim, and E. Zeldov, Science **358**, 1303 (2017).