Vortex dynamics in a strongly interacting two-dimensional superfluid

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Kosterlitz and Thouless were awarded the Nobel Prize for discovering that two-dimensional superfluidity occurs due to a topological phase transition involving the binding of quantized vortices. Quite remarkably, however, even after almost a half century, coherent vortex dynamics have yet to be directly seen in any strongly-interacting two-dimensional superfluid. Here, we address this longstanding challenge, observing the coherent dynamics of nonequilibrium clusters of vortices in two-dimensional helium as they evolve, dissipate and annihilate [1].

The importance of strongly-interacting superfluids ranges from string theory to astrophysics; including dark matter, the quark-gluon plasma in the early universe, and neutron star physics. However, progress is impeded by the lack of an underpinning microscopic theory. There is contentious debate, even at the most basic level. For instance, proposed values for the effective mass of a vortex range from zero to infinity, while it remains unclear whether an Iordanskii force exists between vortices and colocalized normal fluid. Our ability to observe vortex dynamics allows direct tests of these questions in the laboratory. We conclude that, for our experiments, neither a vortex mass nor an Iordanskii force is required.

It had generally been thought that surface interactions would prohibit experiments such as ours in two-dimensional helium. We overcome them by greatly enhancing the coherent interactions between vortices. This is achieved by confining the superfluid orders-of-magnitude more strongly than has previously been possible on the atomically smooth surface of a silicon chip. We further show that thermal vortex diffusion is suppressed by six orders-of-magnitude, verifying a thirty-year-old prediction, and realize laser control and imaging of vortex clusters for the first time in helium, leveraging techniques from quantum optomechanics [2].

By observing coherent vortex dynamics in a strongly-interacting two-dimensional superfluid, and achieving this on a silicon-chip with integrated laser observation and control capabilities, our research opens a pathway to explore the rich dynamics of vortices in strongly-interacting systems, to build new matter-wave quantum technologies on a chip, for laboratory tests of astrophysical phenomena, and to test predictions from quantum turbulence.

[1] Sachkou et al, Coherent vortex dynamics in a strongly-interacting... arXiv (Feb, 2019).

[2] Harris et al, Nat. Phys. 12, 788-793 (2016); McAuslan et al, PRX 6, 021012 (2016); Baker et al, New J. Phys. 18 123025 (2016); Forstner et al, arXiv:1901.05167 (2019).