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Theoretical Study of Quantized Vortices and Quantum Turbulence

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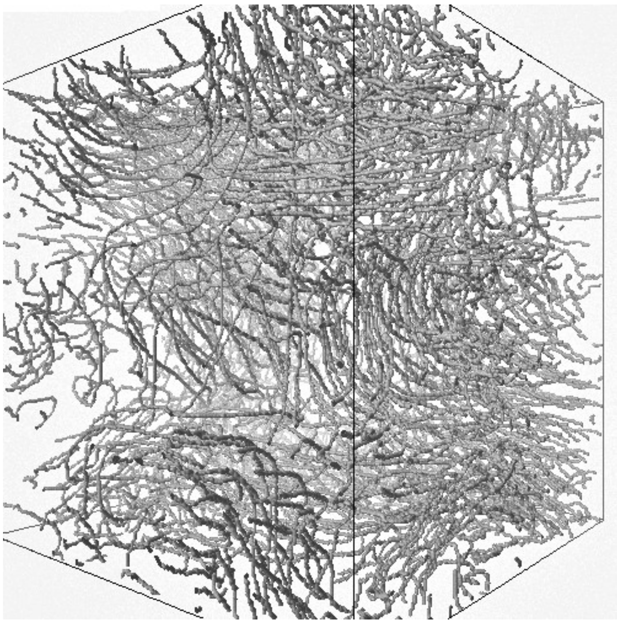
Quantum fluid is hydrodynamic system where quantum effect emerges in macroscopic scales and realized as superfluid helium, ultracold atomic Bose-Einstein condensates, superconductors, and neutron stars. The most important hydrodynamic property of quantum fluid is that any kind of low is either inviscid and irrotational or carried by quantized vortices. Quantized vortices are (i) vortices with a fixed circulation, (ii) stable topological defect without diffusion, and (iii) very thin. Turbulent state of quantum fluid known as quantum turbulence features a spatially and dynamically complicated structure of quantized vortices. Compared with conventional classical turbulence of viscous fluid, quantum turbulence makes investigation of vortex dynamics easier, because quantized vortices are real object unlike eddies in viscous fluid, the structure of which is vague with nucleating and dissipating through the viscosity. We hope that research of quantum turbulence contributes to our knowledge about turbulence by clarifying the relationship between properties of turbulence and behavior of vortices. Here, I talk about two contrasting topics of quantum turbulence obtained by our numerical simulations of the nonlinear Schrodinger equation which describes the dynamics of quantum fluid and quantized vortices.

The first topic is a fully developed quantum turbulence with many quantized vortices under a strong forcing[1,2]. The obtained energy spectrum gives the inertial range having the power law as a classical analogue of quantum turbulence. This inertial range is further separated by the mean inter-vortex distance. In larger scales which are known as the classical region, the inertial range is triggered by cooperative motions of quantized vortices, giving the well-known Kolmogorov's law. In smaller scales than the mean inter-vortex distance known as the quantum region, the inertial range is sustained by helical Kelvin waves excited on each vortex line.

The second topic is the laminar-turbulent transition of quantum fluid with a weak energy injection[3]. In the case of quantum fluid, we can easily separate laminar and turbulent states as a system with or without quantized vortices. Defining the vortex density as the order parameter of turbulence, we can find its power-law behavior with the critical exponent for the non-equilibrium phase transition. The value of the critical exponent is consistent with that for the (3+1)-dimensional directed percolation, which suggests the same underlying physics for two transitions of the directed percolation and quantum turbulence. The key concept is that vortices has a finite energy barrier to be nucleated and cannot be re-nucleated after their extinction.



Example of a spatial vortex configuration for fully-developed turbulence

References:

[1] M. Kobayashi and M. Tsubota, Phys. Rev. Lett. 9**4** 065302 (2005).

[2] M. Kobayashi and M. Ueda, arXiv:1606.07190.

[3] M. Takahashi, M. Kobayashi, and K. A. Takeuchi, arXiv:1609.01561.