

Supplementary Materials: Experimental and theoretical evidence of universality in superfluid vortex reconnections

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EXPERIMENTAL METHOD

To produce solidified deuterium (D_2) tracer particles, we slowly inject a gas mixture of 5% D_2 and 95% 4He into a superfluid helium bath. Our gas injection system is similar to that described by Fonda et al. [1]. A solenoid valve is installed to control the duration of the gas injection, and a needle valve is used to regulate the gas flow rate. The injected D_2 gas solidifies into small ice particles with a mean radius of $1.1 \mu m$, derived from the particle settling velocities in quiescent superfluid helium [2]. A 473 nm continuous-wave laser sheet (thickness: 0.8 mm) illuminates the particles, and their motion in the laser sheet plane is recorded by a camera at 200 frames per second with a maximum resolution of 2560×1440 pixels. We then identify vortex reconnection events from the recorded videos, and manually track the coordinates of the trapped particles for the pre- (if captured) and post-reconnection. Knowing the particle coordinates, the minimum distance between the reconnecting vortices $\delta^\pm(t)$ can be measured. We calculate the prefactors A^\pm using the slopes of linear fits to the $\delta^2(t)$ data.

NUMERICAL METHOD

Using Schwarz mesoscopic model [3], vortex lines can be described as space curves $\mathbf{s}(\xi, t)$ of infinitesimal thickness, with a single quantum of circulation $\kappa = h/m_4 = 9.97 \times 10^{-8} m^2/s$, where h is Planck’s constant, $m_4 = 6.65 \times 10^{-27} kg$ is the mass of one helium atom, ξ is the natural parameterisation, arclength, and t is time. These conditions are a good approximation, since the vortex core radius of superfluid 4He ($a_0 = 10^{-10} m$) is much smaller than any of the

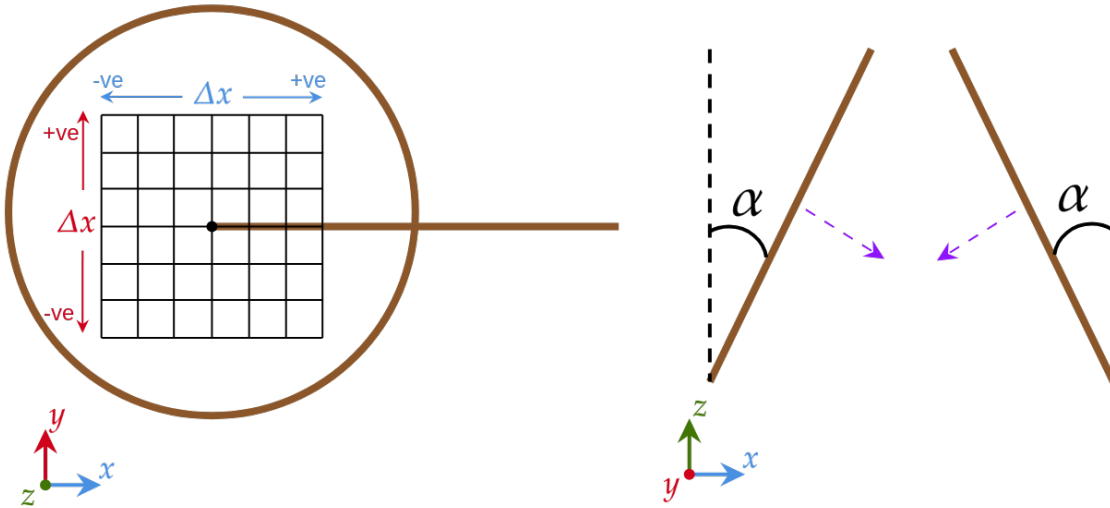


FIG. 1: Schematic diagram for numeric initial condition. *Left*: Hopf-link. *Right*: Oblique collision.

length scale of interest in turbulent flows. The equation of motion is

$$\dot{\mathbf{s}}(\xi, t) = \mathbf{v}_s + \frac{\beta}{1 + \beta} [\mathbf{v}_{ns} \cdot \mathbf{s}'] \mathbf{s}' + \beta \mathbf{s}' \times \mathbf{v}_{ns} + \beta' \mathbf{s}' \times [\mathbf{s}' \times \mathbf{v}_{ns}], \quad (1)$$

where $\dot{\mathbf{s}} = \partial \mathbf{s} / \partial t$, $\mathbf{s}' = \partial \mathbf{s} / \partial \xi$ is the unit tangent vector, $\mathbf{v}_{ns} = \mathbf{v}_n - \mathbf{v}_s$, \mathbf{v}_n and \mathbf{v}_s are the normal fluid and superfluid velocities at \mathbf{s} and β, β' are temperature and Reynolds number dependent mutual friction coefficients [4]. The superfluid velocity \mathbf{v}_s at a point \mathbf{x} is determined by the Biot-Savart law

$$\mathbf{v}_s(\mathbf{x}, t) = \frac{\kappa}{4\pi} \oint_{\mathcal{T}} \frac{\mathbf{s}'(\xi, t) \times [\mathbf{x} - \mathbf{s}(\xi, t)]}{|\mathbf{x} - \mathbf{s}(\xi, t)|} d\xi, \quad (2)$$

where \mathcal{T} represents the entire vortex configuration. There is currently a lack of a well-defined theory of vortex reconnections in superfluid helium, like for the Gross-Pitaevskii equation [5–7]. An *ad hoc* vortex reconnection algorithm is employed to resolve the collisions of vortex lines [8].

A *two-way model* is crucial to understand the accurately interpret the back-reaction effect of the normal fluid on the vortex line and vice-versa [9]. We self-consistently evolve the normal fluid \mathbf{v}_n with a modified Navier-Stokes equation

$$\frac{\partial \mathbf{v}_n}{\partial t} + (\mathbf{v}_n \cdot \nabla) \mathbf{v}_n = -\nabla \frac{p}{\rho} + \nu_n \nabla^2 \mathbf{v}_n + \frac{\mathbf{F}_{ns}}{\rho_n}, \quad (3)$$

$$\mathbf{F}_{ns} = \oint_{\mathcal{T}} \mathbf{f}_{ns} \delta(\mathbf{x} - \mathbf{x}) d\xi, \quad \nabla \cdot \mathbf{v}_n = 0, \quad (4)$$

where $\rho = \rho_n + \rho_s$ is the total density, ρ_n and ρ_s are the normal fluid and superfluid densities, p is the pressure, ν_n is the kinematic viscosity of the normal fluid and \mathbf{f}_{ns} is the local friction per unit length [10]

$$\mathbf{f}_{ns} = -D \mathbf{s}' \times [\mathbf{s}' \times (\dot{\mathbf{s}} - \mathbf{v}_n)] - \rho_n \kappa \mathbf{s}' \times (\mathbf{v}_n - \dot{\mathbf{s}}), \quad (5)$$

where D is a coefficient dependent on the vortex Reynolds number and intrinsic properties of the normal fluid.

The results in this Letter are reported in dimensionless units, where the characteristic length scale is $\tilde{\lambda} = D/D_0$, where $D^3 = (1 \times 10^{-3} \text{m})^3$ is the dimensional cube size, $D_0^3 = (2\pi)^3$ is the non-dimensional cubic computational domain. The time scale is given by $\tilde{\tau} = \tilde{\lambda}^2 \nu_n^0 / \nu_n$, where the non-dimensional viscosity ν_n^0 resolves the small scales of the normal fluid. In these simulations, these quantities are $\tilde{\lambda} = 1.59 \times 10^{-4} \text{cm}$, $\nu_n^0 = 0.16$ and $\tilde{\tau} = 0.183 \text{s}$ at $T = 0 \text{K}$ and at $T = 1.9 \text{K}$ and $\tilde{\tau} = 0.242 \text{s}$ at $T = 2.1 \text{K}$. We consider two distinct initial vortex geometries at $T = 0 \text{K}$, 1.9K and 2.1K . The first is a Hopf link, two linked rings of radius $R \approx 1$ with an offset in the xy -plane defined by parameters Δl_x and Δl_y . The offsets are chosen so that $(\Delta l_x, \Delta l_y) \in \{(0.125i, 0.125j) | i, j = -3, \dots, 3\}$, a total of 49 reconnections for each temperature. The second geometry is a collision of vortex rings of radius $R \approx 1$ in a tent-like configuration (see Fig. 1), making an angle α with the vertical. We take 12 realisations of α , such that $\alpha \in \{i\pi/13 | i = 1, \dots, 12\}$.

In both cases, normal fluid rings are initially superimposed to match the vortex lines, eliminating the transient phase of generating normal fluid structures. The Lagrangian discretisation of vortex lines is $\Delta \xi = 0.025$ (a total of 668 discretisation points) with a timestep of $\Delta t_{VF} = 1.25 \times 10^{-5}$. A total of $N = 256^3$ Eulerian mesh points were used for the normal fluid, with a timestep of $\Delta t_{NS} = 40 \Delta t_{VF}$.

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