during the flooding associated with Hurricane Katrina, and this could be explained by the correlation we observe between the location of breach points and the high rate of subsidence beneath these levee sections (see supplementary information). Our subsidence estimates are probably minimum values considered over the lifetime of the levees, given that subsidence was most rapid in the first few years after their construction in the 1960s. Levee failure may have resulted from overtopping because the levees were too low — data collected after the storm[5] indicate that water levels exceeded those expected by 0.9–1.7m. Alternatively, the high subsidence rates we observe might reflect active faulting or a weak, easily compacted substrate, promoting failure at or near the levee base.

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SUPERFLUID HELIUM

Visualization of quantized vortices

When liquid helium is cooled to below its phase transition at 2.172 K, vortices appear with cores that are only ångströms in diameter, about which the fluid circulates with quantized angular momentum[1]. Here we generate small particles of solid hydrogen that can be used to image the cores of quantized vortices in their three-dimensional environment of liquid helium. This technique enables the geometry and interactions of these vortices to be observed directly.

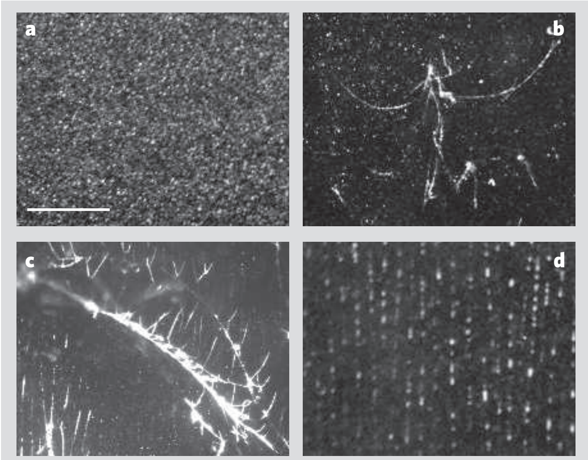

Figure 1 | Quantized vortex cores in liquid helium. a–d, Images of particles (light against dark background) obtained with a camera and 105-mm lens under different conditions: **a,** just above the transition temperature, when they are uniformly dispersed; **b, c,** on branching filaments at tens of millikelvin below the transition temperature; and **d,** regrouping along vertical lines for steady rotation about the vertical axis. In **b** and **c**, the particles on lines are evenly separated in small regions. Scale bar, 1 mm.

Since the discovery of quantized vortices[2], attempts have been made to visualize them. Although the ends of parallel vortices in an array could be located[3], there has been no successful imaging of vortices in arbitrary three-dimensional configurations. Suspended particles can trace fluid motions, and the velocities of frozen particles in superfluid helium have been measured since hydrogen was first condensed for the purpose[4]. These particles usually have diameters larger than 10 μm[5,6], although smaller polymer particles have been used[7].

Our technique generates smaller hydrogen particles by injecting a premixed gaseous solution of hydrogen, greatly diluted with helium, into liquid helium in its normal phase above the transition temperature (for details of methods, see supplementary information). This procedure yields a mist of randomly distributed hydrogen particles (Fig. 1a) that are smaller than the 2.7-μm resolution of our long-range microscope. The suspension so prepared is then cooled to below the transition temperature.

Images taken with a digital camera focused on a thin laser-illuminated sheet show that not only do the particles trace fluid motions, but a fraction of them also collect on slender filaments, which are often several millimetres long (Fig. 1b, c).

Particles respond in a complicated way to superfluid flows[8] and can be trapped in vortex cores[9]. The following evidence suggests that the observed filaments are particles collected on such cores. First, these filaments appear only below the transition temperature. Second, when the liquid-helium cell is set in steady rotation, the particles arrange themselves along uniformly spaced lines (Fig. 1d). The lines are parallel to the axis of rotation, which is in the image plane. This observation agrees with the expectation that quantized vortices form a rectilinear array aligned with the axis[1]. Third, if we assume that our sheet illuminates a slice of such an array, we find that the number density of lines per unit area normal to the axis of rotation, for a series of rotation rates, is consistent with Feynman's rule[10], which predicts about 2,000Ω lines per cm^2, where Ω is the angular velocity of the container in radians per second.

The filaments are complex: for example, they may give rise to branched networks and to particles evenly spaced along lines. Others have speculated how particles could act as passive tracers of the flow[7,8]; our images indicate that the presence of particles in the superfluid may transform the topology of vortex tangles by stabilizing forks in the vortices. This technique offers a tantalizing glimpse of new phenomena for future investigation.

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