

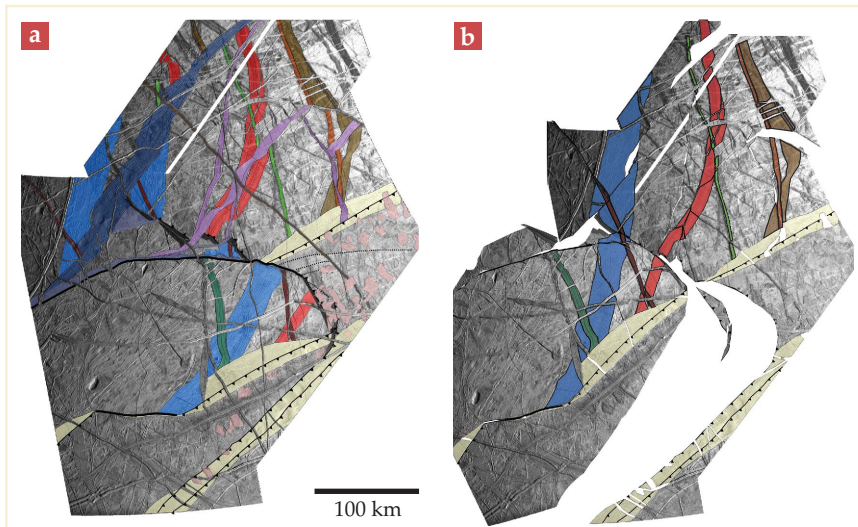


Figure 2. Turning back time on tectonic plates. (a) In this 134 000-km² region of Europa, relevant geological features are highlighted in color: young dilational bands in purple and dark blue, newly identified subduction bands in light beige, and older structures in other colors. (b) Undoing the effects of a possible tectonic process yields this reconstruction. The large white gap and the abrupt termination of the older geological features suggest that portions of crust have been lost to subduction. (Adapted from ref. 1.)

that the icy plate once filling that area has been pushed underneath another in the subduction zone along the lower right edge of the region. Furthermore, the blue, green, red, and brown features all end abruptly at the subduction zone across the middle of the region; no continuation of any of them can be found anywhere in the plates on the other side. The researchers conclude that parts of those features have also been lost to subduction.

Falling ice?

Whether subduction occurs anywhere else on Europa apart from the small area in figure 2 remains to be seen. If it does occur elsewhere, Europa could provide insight into which aspects of plate tectonics are general and which are specific to Earth. One difference is already clear: Terrestrial tectonic plates are made of rock, and European plates are made of ice. On Earth, cold oceanic crust is often denser than the hot silicate mantle, and it becomes denser still as its mineral form changes under pressure. As a result, subducting slabs can sink into the deep mantle, further shifting the attached crustal plates in the process.

But buoyancy prevents Europa's crust from descending into the liquid-water ocean that lies underneath. It's not clear what forces would drive the plate motions in that scenario. Kattenhorn and Prockter hypothesize a model in which only the outermost layer of

Europa's ice shell—the coldest, densest, most brittle ice—is divided into plates. Subducting plates then could still be pulled downward through a layer of warmer, slushier, less dense ice. The researchers propose the term “subsumption” to describe the process and differentiate it from terrestrial subduction, but they stress that the theory has yet to be worked out.

Europa's ocean is thought by many to be one of the most likely homes in the

solar system for extraterrestrial life. Of the three ingredients necessary for life as we know it—liquid water, energy, and the right chemical building blocks—Europa has plenty of the first two, thanks to tidal heating by Jupiter, but its chemical environment is largely unknown. The ions and electrons trapped in Jupiter's magnetosphere bombard Europa's surface, producing molecular oxygen, ozone, hydrogen peroxide, and other oxidants.⁵ But for those molecules to drive the chemical reactions of life, some mechanism needs to transport them from the surface into the ocean. Subduction (or subsumption) could do just that.

Solving Europa's mysteries will require a new spacecraft to visit the moon and collect more data. The Europa Clipper, a NASA mission concept currently under study, promises a treasure trove of high-resolution images and other measurements—but not for at least 15 years. In the meantime, Kattenhorn and Prockter's analysis suggests that undiscovered clues may still be hiding in the images from *Galileo*.

Johanna Miller

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Quantized vortices in a nanodroplet

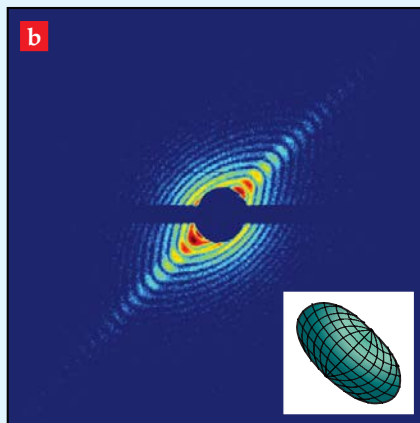
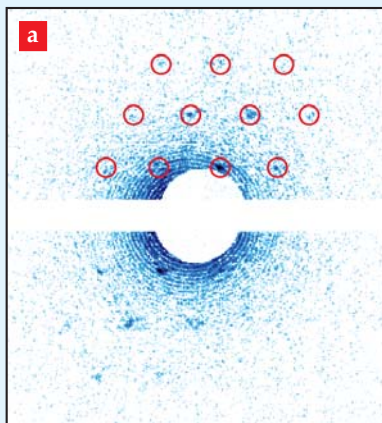
Diffraction experiments reveal hidden order inside a spinning superfluid.

Spin a vessel of water and, in time, the fluid will rotate as a rigid body, everywhere circling with the same angular velocity. Replace the water with a superfluid—a liquid chilled to a viscosity-free quantum state—and the flow instead spawns quantum tornadoes, vortices in which fluid circulates with quantized angular momentum.

First predicted more than a half century ago, quantized vortices have been studied extensively in experiments with rotating cryostats of liquid helium. They are thought to underlie such exotic phenomena as quantum turbulence (see the article by Joe Vinen and Russell Donnelly, *PHYSICS TODAY*, April 2007, page 43), and they've been shown to re-

connect in a fashion analogous to the magnetic reconnections that instigate solar flares.

When it comes to elucidating the underlying physics of rotating superfluids, however, cryostats have their limitations. Defects along the container's surface inevitably disturb the flow in ways that can't be neatly captured by theory. Plus, bulky cryostats can be spun only so fast, typically no more than a few rotations per second. Many interesting phenomena are thought to emerge at higher angular velocities. Now an international collaboration led by Christoph Bostedt (SLAC), Oliver Gessner (Lawrence Berkeley National Laboratory), and Andrey Vilesov



X-ray diffraction images hint at the flow structure and shape of micron-sized superfluid droplets. **(a)** A triangular lattice of Bragg peaks, circled in red, reveals an ordered array of quantized vortices in one droplet. **(b)** In an image of a different droplet, oblong interference fringes indicate that the droplet has bulged at its equator and flattened at its poles, as sketched in the inset. (Adapted from ref. 1.)

(University of Southern California) reports the detection of quantized vortices in fast-spinning, container-free versions of rotating vessels: liquid-helium nanodroplets.¹

Vilesov first began working with droplets two decades ago, as a postdoc in J. Peter Toennies's lab at the Max Planck Institute for Dynamics and Self-Organization in Göttingen, Germany. There the researchers figured out that if they cooled helium-4 to about 15 K and sprayed it into a vacuum, they could make a beam of helium nanodroplets. Friction with the nozzle sets the droplets spinning at up to millions of rotations per second, and evaporative cooling chills them to a superfluid state. (See the article by Toennies, Vilesov, and Birgitta Whaley, *PHYSICS TODAY*, February 2001, page 31.)

The team verified the droplets' superfluidity—at least at molecular length scales—by seeding them with sulfur hexafluoride: The immersed molecules exhibited sharp rotational peaks in their IR spectra; in a normal fluid, those modes would have been damped by viscous forces.² Less obvious was how one might image the quantized vortices—if they even existed. Some theories held that the vortices would be unstable or energetically unfavorable in such tiny droplets.

Portrait of a superfluid

Encouraged by recent developments in ultrafast imaging with free-electron lasers, Bostedt, Gessner, and Vilesov hatched a plan to look for the vortices using x-ray diffraction. The idea was to dope the droplets with xenon atoms, which tend to cluster along the vortex cores and provide x-ray scattering contrast. Assuming the vortices settle into

ordered arrays, as they do in rotating cryostats, they might show up in diffraction patterns as Bragg peaks.

The researchers secured a week of beam time at SLAC's Linac Coherent Light Source, where they imaged thousands of droplets, one at a time, by spraying them through the pulsed laser's focal volume. Panel a in the figure shows an image taken head-on along a droplet's spin axis. The triangular lattice of Bragg peaks is indicative of a triangular array of vortices, their cores aligned with the droplet's spin axis. From the spacing between peaks, the researchers estimate that the droplet, 2 μm in diameter, contained roughly 160 vortices and was spinning about 350 000 times a second.

Panel b shows another droplet, just 800 nm in diameter, imaged from the side. The oblong fringes result from diffraction by the helium droplet itself: The more widely spaced fringes in the northeast-southwest direction indicate that the droplet is narrower in that direction; the narrowly spaced fringes in the northwest-southeast direction indicate the droplet is wider. By inverse Fourier transform, the team obtained the sketch shown in the inset. As expected, the spinning droplet bulges at its equator, but the extent of the deformation is surprising: Twice as wide as it is tall, the droplet has bulged so severely as to flatten at its poles. From that shape profile, the researchers estimate that the droplet was rotating more than 2 million times per second. At equivalent angular velocities, a classical droplet would have begun to pull apart to form a two-lobed, peanut-like structure, with the spin axis piercing the peanut's waist.³

Curiously, fast-spinning droplets

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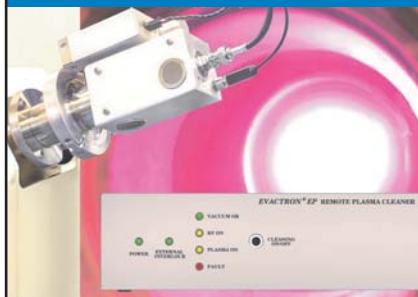
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like the one imaged in panel b don't display Bragg peaks. The researchers suspect that could be a sign of new physics—perhaps a transition to a disordered or nonstationary phase or the onset of an unidentified hydrodynamic instability. The answer may be buried somewhere in the data. “So far we’ve analyzed less than 5 percent of our images—the ones that show the most intense, well-defined Bragg spots,” says Vilesov. “But many of the other images

show more complex diffraction patterns, and presumably those will also tell us something about the vortex arrangements. Hopefully, there are more surprises to come.”

Ashley G. Smart

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Collaboration unlocks self-replicating crack patterns

A novel fracture mechanism sets new limits for thin-film stability.

Surface coatings, found on everything from painted walls to computer chips, often build up residual stresses during deposition, drying, or mechanical loading. If the stresses become large enough, the film can fracture, which typically leads to a disordered crack pattern. But under the right conditions, regular patterns like the ones in the optical microscope images shown on page 19 can appear.

Joël Marthelot (now at MIT), Benoît Roman, and José Bico of ESPCI Paris-Tech, along with their colleagues from the Saint-Gobain Corp and the University of Santiago, have taken a close look at the formation of such cracks. The material they studied was so-called spin-on glass (SOG)—a silicate coating commonly used for electronic components—deposited on a silicon substrate. What they discovered was a new fracture mechanism that has implications for understanding the stability of thin films and offers the possibility of novel applications.¹

Although unusual, the crack patterns aren't new.² In fact, Roman and Bico were introduced to them in 2006 by Melanie Lebental of École Normale Supérieure de Cachan. Lebental had been using SOG as an optical buffer layer for microlaser cavities as part of her PhD work when she noticed a sample covered with crescent-shaped cracks that zigzagged back and forth. “I had never heard of such cracks,” Lebental says. So she showed them to a friend, who introduced her to Roman. She visited Roman and Bico in their lab: “I gave them a sample with cracks, a small bottle of SOG, and the procedure to get the cracks.”

Lebental's crack patterns looked sim-

ilar to ones that Roman had studied before,³ but those were produced by running a blunt cutting tool through brittle sheets with no substrate. (For more on the elastic properties of thin sheets, see the article by Michael Marder, Robert Deegan, and Eran Sharon, *PHYSICS TODAY*, February 2007, page 33.) “So the problem here was clearly different,” Roman says.

A tale of two cracks

Crack formation in thin films is usually a matter of competition between elastic energy and fracture energy. Residual tensile stresses often build up during film deposition and processing. If they grow large enough, the elastic energy released by cracking can overcome the energy needed to break the film. In the standard picture, the film fractures along isolated straight lines and stress is released only near the crack. New cracks tend to turn and run into old cracks perpendicularly. The result is the kind of crack pattern commonly seen in drying mud or varnish on old paintings. (For more, see the article by Lucas Goehring and Stephen Morris on page 39.)

For a given film and substrate, the elastic energy is a function of stress and film thickness. So the balance between elastic energy and fracture energy prescribes a critical film thickness, below which an isolated crack shouldn't propagate. But in their new study, Marthelot and company saw their nonstandard crack patterns even in films thinner than the critical thickness, which was 1.8 μm in their case.

The explanation came from realizing that the rules change for a pair of cracks. Two cracks running next to each other can release additional stress by having