

Classical precursor to turbulence observed in a superfluid

An obstacle dragged through a Bose–Einstein condensate can leave a well-known pattern of vortices in its wake.

A stirred cup of coffee, like any normal fluid, can swirl around with an arbitrary speed and angular momentum. That's not the case for superfluids. They can rotate only by winding themselves in vortices whose circulation is quantized. Mathematically, the vortices are simply zero-density points or lines around which the wavefunction's phase wraps by integer multiples of 2π (see the article by Joe Vinen and Russell Donnelly, *PHYSICS TODAY*, April 2007, page 43). That constraint has turned superfluids such as liquid helium and Bose–Einstein condensates (BECs) into model systems for studying turbulence, largely because the quantized vortices that embody that messy state in a superfluid are themselves discrete, well defined, and detectable.¹

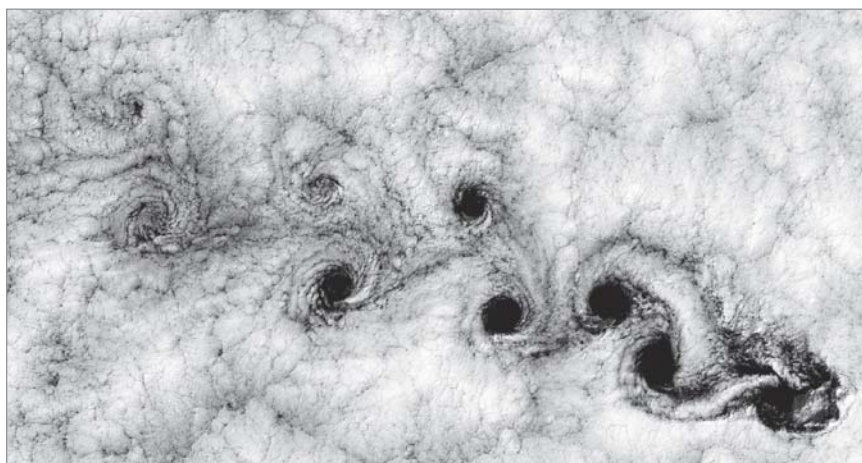


FIGURE 1. A VON KÁRMÁN VORTEX STREET is the periodic chain of countercirculating eddies that can form in the wake of a fluid moving over an obstacle. In this case, a satellite captured the pattern in the movement of clouds flowing over an island off the coast of Chile. (Courtesy of NASA.)

Because their vortices can be directly caught on camera, BECs are particularly appealing to study. The dilute atoms interact so weakly that the extent of the especially low-density region around a vor-

tex can be as large as a micron; in liquid helium, it's on the scale of an angstrom. Vortex size is set by the quantum pressure exerted by a fluid; the higher the density and interaction strength, the higher



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the pressure. Furthermore, once the magnetic potential used to confine the BEC is turned off, the atomic gas (and thus the vortices) expands to a few times its original size within milliseconds. When the gas is illuminated with visible light, the vortices show up as dark, density-depleted holes.

Researchers led by Yong-il Shin (Seoul National University) have now exploited that shadow-imaging technique to investigate the transition between laminar

and turbulent flows in an oblate BEC of sodium-23 atoms.² Importantly, their experiments were designed to produce a classic phenomenon in fluid dynamics: the wake behind a moving obstacle. That design allowed them to address a central question in the field: Is superfluid turbulence relevant to the wider world of normal-fluid turbulence? Reassuringly, the group's results affirm a deep connection between quantum turbulence and its classical counterpart.

Turbulence from an obstacle moving in a normal fluid emerges from the competition between viscous and inertial forces. The competition is encapsulated in the Reynolds number Re , a dimensionless quantity equal to the product of an obstacle's relative velocity and width, divided by the viscosity of the fluid. At low Re , the flow past the obstacle is smooth; at high Re , it's a chaotic mess. But between the extremes lies a range of Re over which the wake becomes asymmetric yet ordered: a space- and time-periodic pattern of alternating eddies known as a von Kármán vortex street.

Physicist and engineer Theodore von Kármán explained the stability of the eponymous street in 1911. Shown in figure 1, the pattern has long been associated with such normal-fluid behavior as wind blowing past a tall building or clouds flowing over an island. Eddies peel off one side of an obstacle and then the other before being carried downstream. The alternating pressure swings, which impart vibrations to towers, airplane wings, bridges, chimneys, and myriad other obstacles, can be catastrophic if they are not compensated for (see the Quick Study by Peter Irwin, PHYSICS TODAY, September 2010, page 68).

In their new work, Shin and colleagues identify a narrow velocity regime in which a von Kármán vortex street emerges in their BEC. To pull off that feat—the first experimental demonstration of the iconic classical pattern in any superfluid—the researchers chose a focused laser beam as the obstacle to drag through their BEC, as shown in figure 2. As a mirror steered the beam, they monitored the evolution of vortex-shedding patterns as a function of beam velocity.

Normal and super

Superfluids are completely inviscid, though, which makes Re an undefined quantity. Zero viscosity would imply an infinite Re and thus a form of dissipationless, eternal turbulence. Yet numerous experiments on superfluid He confirm that its turbulent state—a tangle of vortex lines—decays in time, even at temperatures of a few millikelvin.³

In 1953 Lars Onsager realized that the quantized circulation of a superfluid vortex, given by the ratio of Planck's constant h to the atomic mass m , has the same dimension as viscosity. He suggested

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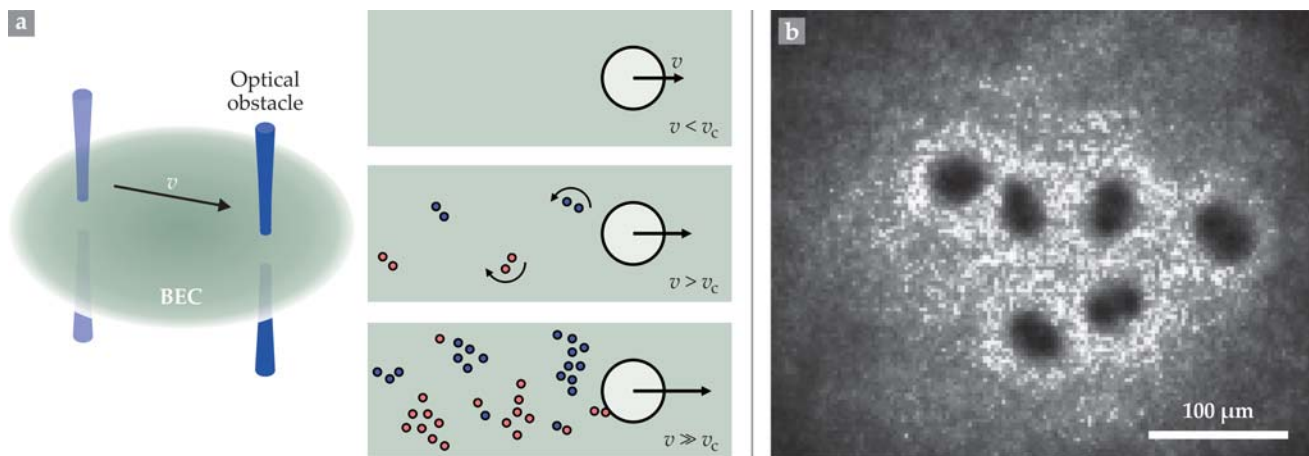


FIGURE 2. EVOLUTION OF VORTEX SHEDDING IN A BOSE-EINSTEIN CONDENSATE. (a) If a repulsive potential at the focus of a laser beam is slowly scanned across a BEC (left), at a velocity v below some critical velocity v_c , the flow of atoms around it is laminar and no vortices appear (right). Just above v_c , like-signed (blue or red) vortices are nucleated and shed from alternating sides of the potential as corotating clusters. Much above v_c , the clusters interact strongly enough to turn the flow turbulent. (b) In this experimental demonstration, a 10- μm -wide beam was moved at 1.6 mm/s across a BEC of sodium atoms, and then the BEC was allowed to expand. Each of the six dark regions is a cluster containing two vortices. (Adapted from ref. 2.)

that quantum-vortex nucleation may provide a kind of emergent viscosity. Such vortex nucleation generates sound waves, so one can think of vortices as topological excitations—localized points where superfluidity breaks down—that give rise to dissipation above some critical obstacle velocity. Two years ago, Matthew Reeves, his thesis adviser Ashton Bradley (both at the University of Otago in New Zealand), and their colleagues took Onsager’s insight as the basis for a modified Re applicable to a BEC and invoked it to simulate the transition to turbulence in the wake of a cylinder.⁴ Among other features, the study predicted the telltale von Kármán vortex street pattern above a critical value of their modified Re .

Shin and colleagues’ experiments come on the heels of the New Zealand study and two earlier simulations⁵ that also predicted the classical wake pattern in a BEC. As with the simulations, the new experimental images clearly showed that just above a critical velocity, individual vortices and pairs of like-signed vortices are nucleated at and then peel away from alternating sides of the moving obstacle (see figure 2a). As the speed increases, so does the rate at which vortices are produced and shed from the obstacle.

The behavior that emerges is one in which individual vortices coalesce into distinct clusters of corotating vortices; at low velocities, such clusters might contain two or three vortices, and at high velocities, they contain many more, which blur together in images as ever-larger

density-depleted holes. According to Nick Parker (Newcastle University), “The formation of those clusters is the key ingredient in how the superfluid can mimic classical flow patterns, and it confirms the intuition that classical physics is reproduced with sufficient quanta.”

Statistical evolution

Because each vortex is quantized, so is the size of each of the holes. That convenient feature of superfluid flow allowed Shin and company to count the number of vortices in each of the clusters they captured during repeated trials at a given obstacle speed. When they prepared a vortex-number probability distribution for a range of velocities, the statistics bore out a transition to turbulence: At speeds just above the critical velocity, the distribution had a narrow peak at one vortex per cluster, but as the speed rose, the distribution widened until, at the fastest speed, it became almost completely flat.

The statistical counting was essential to quantify the transition, because the specific cluster patterns the researchers found even slightly above the critical velocity were “highly stochastic,” Shin says. For instance, the pattern in figure 2b, with just two vortices in each of its six clusters, was reproduced in only 5% of their trials. That’s partly because vortices interact with each other nonlinearly and, if too closely spaced, can quickly distort an emerging pattern into unrecognizable blobs. The vortices’ interactions with borders of the BEC also

contribute. At a mere 300 μm wide, the Seoul group’s condensate offered little room for producing a stable pattern from a 10- μm -wide obstacle.

Another complication is that Shin’s team used a conventional harmonic potential to trap its BEC. As a result, the condensate density varied by as much as 35% as a function of position. No doubt such variations would make the velocity range over which the von Kármán vortex street appears dependent on the track taken by the obstacle. Over the roughly 1.0–2.0 mm/s range of velocities Shin’s group investigated, the classical pattern was found in a narrow 0.1 mm/s window.

Fortunately, though, the size and shape of a BEC’s confining potential is tunable, as is the size of the BEC itself. With the control Shin has over other knobs, such as temperature, dimensionality (less oblate condensates have more three-dimensional character), and the size of the laser beam, he envisions some creative experiments ahead to test the universality of vortex-shedding dynamics.

Mark Wilson

References

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