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New mechanism found for generating giant vortices in quantum fluids of light

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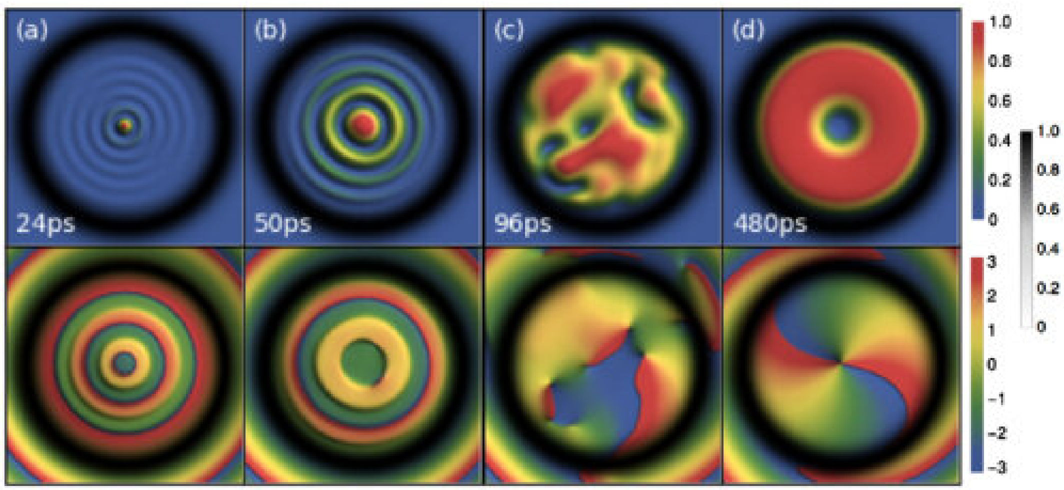

Spontaneous formation of a multiply charged quantum vortex in a ring pumped polariton condensate by numerical integration of Eqs. (3) and (4). Density (top row) and phase (bottom row) snapshots are shown at various stages of the condensate formation. For clarity, each density profile is rescaled to unit maxima. The pumping profiles are superposed in black (in units of P), showing the spatial separation between the pump and the condensate. (a) At the beginning of the condensate formation, due to the pump geometry, matter wave interference leads to annular zeros in the wavefunction. (b) These ring singularities are unstable to dynamical instability, become asymmetrical and can be observed to break into more stable unit vortices as the condensate continues to develop. (c) The condensate fills a disk shaped region with near uniformity within the ring pump, but remaining vortices interact chaotically. The vortex turbulence eventually decays, leaving a net topological charge [48,49]. Repeating these simulations with different random initial conditions, the magnitude and sign of the final vorticity vary. Here, Anyone who has drained a bathtub or stirred cream into coffee has seen a vortex, a ubiquitous formation that appears when fluid circulates. But unlike water, fluids governed by the strange rules of quantum mechanics have a special restriction: as was first predicted in 1945 by future Nobel winner Lars Onsager, a vortex in a quantum fluid can only twist by whole-number units.

These rotating structures are predicted to be widely useful for studying everything from quantum systems to black holes. But while the smallest possible quantum vortex, with a single unit of rotation, has been seen in many systems, larger vortices are not stable. While scientists have attempted to force larger vortices to hold themselves together, the results have been mixed: when the vortices have been formed, the severity of the methods used have generally destroyed their usefulness.

Now, Samuel Alperin and Professor Natalia Berloff from the University of Cambridge have discovered a theoretical mechanism through which giant quantum vortices are not only stable but form by themselves in otherwise near-uniform fluids. The findings, published in the journal *Optica*, could pave the way for experiments that might provide insight into the nature of rotating black holes that have similarities with giant quantum vortices.

To do this, the researchers used a quantum hybrid of light and matter, called a polariton. These particles are formed by shining laser light onto specially layered materials. "When the light gets trapped in the layers, the light and the matter become inseparable, and it becomes more practical to look at the resulting substance as something that is distinct from either light or matter, while inheriting properties of both," said Alperin, a Ph.D. student at Cambridge's Department of Applied Mathematics and Theoretical Physics.

One of the most significant properties of polaritons comes from the simple fact that light can't be trapped forever. A fluid of polaritons, which requires a high density of the exotic particles, is constantly expelling light, and needs to be fed with fresh light from the laser to survive. "The result," said Alperin, "is a fluid which is never allowed to settle, and which doesn't need to obey what are usually basic restrictions in physics, like the conservation of energy. Here the energy can change as a part of the dynamics of the fluid."

It was exactly these constant flows of liquid light that the researchers exploited to allow the elusive giant vortex to form. Instead of shining the laser on the polariton fluid itself, the new proposal has the light shaped like a ring, causing a constant inward flow similarly to how water flows to a bathtub drain. According to the theory, this flow is enough to concentrate any rotation into a single giant vortex.

"That the giant vortex really can exist under conditions that are amenable to their study and technical use was quite surprising," Alperin said, "but really it just goes to show how utterly distinct the hydrodynamics of polaritons are from more well-studied quantum fluids. It's exciting territory."

The researchers say that they are just at the beginning of their work on giant quantum vortices. They were able to simulate the collision of several quantum vortices as they dance around each other with ever increasing speed until they collide to form a single giant vortex analogous to the collision of black holes. They also explained the instabilities that limit the maximum vortex size while exploring intricate physics of the vortex behavior.

"These structures have some interesting acoustic properties: they have acoustic resonances that depend on their rotation, so they sort of sing information about themselves," said Alperin. "Mathematically, it's quite analogous to the way that rotating black holes radiate information about their own properties."

The researchers hope that the similarity could lead to new insights into the theory of quantum fluid dynamics, but they also say that polaritons might be a useful tool to study the behavior of black holes.

More information: Samuel N. Alperin et al. Multiply charged vortex states of polariton condensates, *Optica* (2021). DOI: 10.1364/OPTICA.418377

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