Physicist studies concepts affecting fluids at different scales

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On the wall of Prof. Paul Wiegmann's office hang two large, artistically rendered photographs of fluid vortices. One shows one big vortex, while the other depicts many vortices moving collectively.

A Chicago modern artist gave the photographs to Wiegmann after learning of his scientific interest in vortices. The photographs symbolize Wiegmann's interest in fluids of all kinds: electronic fluids, superfluid helium and even ordinary water.

"Fluids consist of particles, and usually the characteristics of those particles are not really important, but we observe and are interested only in their collective behavior, which typically is indifferent to the property of each particle," said Wiegmann, the Robert W. Reneker Distinguished Service Professor in Physics. And that behavior is the same, whether the vortices consist of electrons in a semiconductor device, or the turbulent flow of gas in a car cylinder, or water on a lake behind a spinning motorboat propeller.

Wiegmann is spending this academic year as a Simons Fellow in Theoretical Physics. His Simons project evolved from a graduate course that he teaches on topology and geometry in physics.

In water, a spinning vortex exemplifies a topological characteristic, a geometric configuration that resists deformation via stretching or twisting. How does a large collection of vortices behave? That's one of the effects of geometry and topology in physics that Wiegmann seeks to understand. The focus of his Simons Foundation Fellowship research, however, is the collective behavior of electrons in an exotic quantum fluid rather than of ordinary liquid vortices.

Remarkable collectivity

The electronic particles of a quantum fluid live rather scientifically unremarkable individual lives, yet manifest quite interesting features collectively.

"One of the most dramatic phenomena of this kind is the fractional quantum Hall effect, which is seen in semiconductors under the influence of a very strong magnetic field," Wiegmann said.

The effect is based on the observation of quantum Hall conductance, which allows scientists to obtain the fine-structure constant—a measure of the strength of the electromagnetic force that governs the interaction of electrically charged particles and light—to a precision of nine digits to the right of the decimal point.

"But the system in which they measure this is imprecise and mostly unknown," Wiegmann noted. That begs the question: How can such an amazingly precise measurement stem from such a dirty, imprecise, unknown and uncontrollable material?

The phenomenon possibly depends not on the material's properties, but on the collective behavior of the material's constituents. "The details of the imprecision then become irrelevant," Wiegmann said.

The topology of quantum spaces plays an important role in understanding the phenomenon. Although the subject matter is rather abstract and mathematically theoretical, it can lead to particular phenomena that scientists can measure in the laboratory.

Theoretical perspective

During his Simons Fellowship, Wiegmann seeks to understand this one known example better from a theoretical perspective, but he also seeks new examples. He thus is applying the same mathematics to other physical phenomena, mostly in fluids, to see if that may lead to laboratory measurements as precise as those known for the quantum Hall effect. This has led to his collaboration with William Irvine, associate professor in physics. With Wiegmann's theoretical support, Irvine has been developing an experimental system for studying classical topological fluids using a collection of spinning magnets in water.

"We're in the process of ironing out some of the first glitches that you come across when you implement a new system," Irvine said. The question is whether they can design a system of classical fluids—ordinary liquids or gases—that have topological properties. But these properties usually are associated with exotic quantum states that exist only under extreme conditions.

These topological properties give rise to a different behavior of fluids near their boundaries, because that's where vortices and eddies form. "And that's going to change the state of the fluid very dramatically," Irvine said.

Topological behavior is in fact a hallmark property of the quantum Hall effect that has been observed in ultracold, exotic electronic matter.

"One of these properties is called anomalous viscosity," Irvine said. This type of viscosity is odd because the fluid doesn't lose energy as it normally would when it flows.

"It's intriguing to see whether or not you can reverse engineer the topological aspects into a classical fluid, because then it would behave very differently at the boundary," Irvine said. "Who knows what that will do? We don't have an explicit prediction, but we think it might suppress or enhance some development of the turbulence."

Spring-coupled gyroscopes

Irvine and his team recently reported their experimental data on a mechanical system that mimics a topological property. That 2015 study, published in the *Proceedings of the National Academy of Sciences*, involved an artificial structure consisting of spring-coupled gyroscopes.

When the researchers poked an artificial solid, instead of getting sound waves going through it, the sound waves stayed localized to the surface and went around the object in one direction only, Irvine explained. "With Paul we're trying to do something that is a little harder, which is the fluid equivalent of that."

The goal, Wiegmann said, is to link his abstract ideas in theoretical physics with Irvine's laboratory experiments to create new materials with unusual, controlled properties. And it all reflects Wiegmann's and Irvine's unusual approaches to physics.

More information: Lisa M. Nash et al. Topological mechanics of gyroscopic metamaterials, *Proceedings of the National Academy of Sciences* (2015). DOI: 10.1073/pnas.1507413112

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