The observation of Kardar-Parisi-Zhang hydrodynamics in a quantum material

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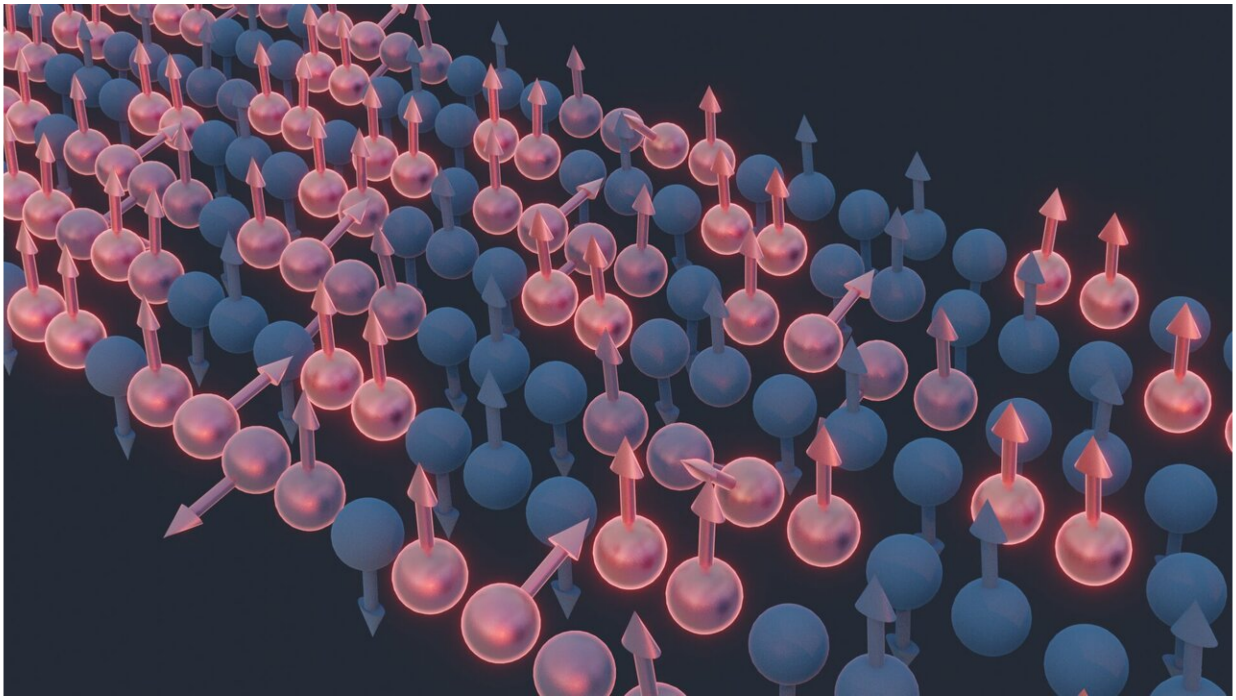

An array of independent spin chains that conduct heat and spin along their length. Quasiparticles shown in red interact and collide with each other forming a strange fluid with KPZ universality emerging on long distances and times. Credit: Oak Ridge National Laboratory, U.S. Dept. of Energy.

Classical hydrodynamics laws can be very useful for describing the behavior of systems composed of many particles (i.e., many-body systems) after they reach a local state of equilibrium. These laws are expressed by so-called hydrodynamical equations, a set of mathematical equations that describe the movement of water or other fluids.

Researchers at Oak Ridge National Laboratory and University of California, Berkeley (UC Berkeley) have recently carried out a study exploring the hydrodynamics of a quantum Heisenberg spin-1/2 chain. Their paper, published in *Nature Physics*, shows that the spin dynamics of a 1D Heisenberg antiferromagnet (i.e., $KCuF_3$) could be effectively described by a dynamical exponent aligned with the so-called Kardar-Parisi-Zhang universality class.

"Joel Moore and I have known each other for many years and we both have an interest in quantum magnets as a place where we can explore and test new ideas in physics; my interests are experimental and Joel's are theoretical," Alan Tennant, one of the researchers who carried out the study, told Phys.org. "For a long time, we have both been interested in temperature in quantum systems, an area where a number of really new insights have come along recently, but we had not worked together on any projects."

A while back, when Moore visited Oak Ridge National Laboratory to participate in the creation of the institute's quantum science center, he shared some of his ideas with Tennant. He specifically told Tennant about a fascinating hypothesis he was exploring related to the extraordinary ways in which hydrodynamics may develop in quantum spin chains.

Tennant, who had already carried out a number of studies investigating the emergence of hydrodynamics in two- and three-dimensional magnets, was highly intrigued by Moore's hypothesis. Eventually, they decided to collaborate on a research project exploring this new idea.

The researchers' measurements were made on a high-quality single crystal of potassium copper fluoride. The neutrons scatter from the quantum spins of the copper sites. The scattering is then analyzed to extract the spin transport along the chains. Credit: Oak Ridge National Laboratory, U.S. Dept. of Energy.

"The reason I had been interested in hydrodynamics was the question of how our classical laws of behavior evolve over length scales from quantum interactions at the atomic scale," Tennant said. "Joel's key point was that there were a very large number of conservation laws hidden in the dynamics of the Heisenberg chain, which would mean the quantum effects at the atomic scale would be felt on the meso and microscales. I had worked for decades on spin chains and thought we had a pretty good understanding of them, so this was something I was very keen to test, as it brought a completely new perspective."

As part of the recent study, Nick Sherman and Maxime Dupont, two physicists from Moore's research group at UC Berkeley, carried out a number of simulations aimed at showing the hydrodynamics in a quantum spin chain. These simulations unveiled an unusual scaling form of the scattering in a region of energy and wavevector that the researchers had previously ignored.

"It seemed very challenging to reproduce these simulations experimentally, but I knew no one had ever undertaken experiments in the conditions needed, so there was a chance of finding something interesting," Tennant said.

To conduct their experiments, Tennant, Moore and their colleagues decided to use $KCuF_3$, a renowned and widely investigated 1D Heisenberg antiferromagnet. To measure correlations, they used a technique known as time-of-flight neutron scattering, specifically focusing on very small frequencies at high temperatures.

"We needed a very good resolution and both Allen Scheie (the postdoc who did much of the work on the project) and I were skeptical of whether we would see the effect we hoped to observe," Tennant said. "We treated the experiment very much as a test run, but it was apparent quickly that there may well be the predicted scaling there."

Aerial view of the Spallation Neutron Source at Oak Ridge National Laboratory where the neutron scattering experiments were undertaken on the SEQUOIA instrument. Credit: Oak Ridge National Laboratory, U.S. Dept. of Energy.

The data gathered by the researchers had to be carefully handled and treated, also to account for the effects caused by background noise or poor resolution. Ultimately, however, Tennant and his colleagues clearly observed a signal hinting to the scaling they predicted.

In their experiment, the team heated up $KCuF_3$ until it became a dense interacting gas of quantum quasiparticles. They then used neutrons to probe how the material carried spin over long distance and time scales by relating the scattering they observed to magnetic correlations.

"We observed the Kardar-Parisi-Zhang universal behavior, famous from a wide range of non-quantum systems, in a quantum material," Tennant said. "This observation confirms an important hypothesis linking the emergence of macroscopic behavior from the atomic scale. The physics involved are incredibly complex, so to show that general principles are at play that allow quantitative predictions to be made is important."

Physicists still have a poor understanding of heat and spin transport in quantum materials. However, some studies led to unexpected observations of so-called 'strange fluid' behavior in these systems.

Tennant and his colleagues identified one example of this unusual behavior that could be explained by existing physics theory. In the future, the experimental approach and techniques they used could also be applied to other materials, which could ultimately broaden the current understanding of these materials and their hydrodynamics.

"We are now working on using magnetic fields to disrupt the conservation laws responsible for the Kardar-Parisi-Zhang behavior to explore its breakdown to conventional ballistic and diffuse transport behavior," Tennant said. "We are also looking at materials with larger quantum numbers, which should be more classical. Finally, we will apply the experimental approach to other magnets such as spin liquids, where it is important to understand the emergence of transport behavior from the atomic scale interactions."

More information: Detection of Kardar-Parisi-Zhang hydrodynamics in a quantum Heisenberg spin-1/2 chain. *Nature Physics*(2021). DOI:

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