Researchers confirm decades-old theory describing principles of phase transitions

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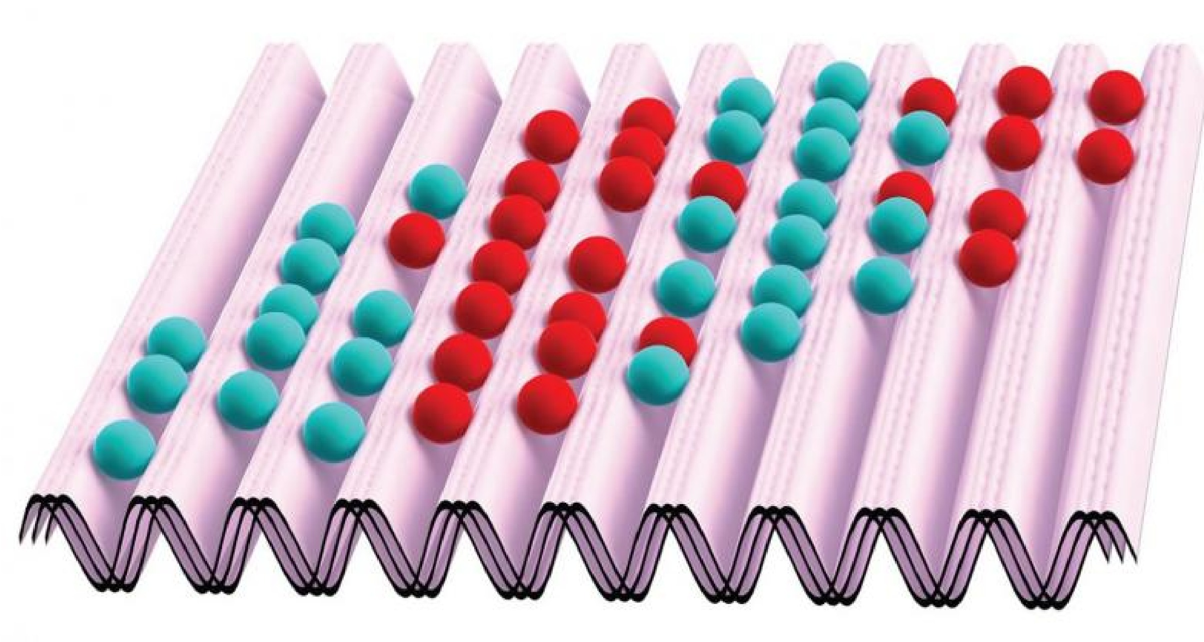

In an experiment at UChicago that witnessed a phase transition of quantum cesium atoms, an optical lattice lined the atoms up in patterns based on their positive or negative momentum. The lattice was shaken to drive the atoms across the phase transition and divide into different domains. Credit: University of Chicago

New research conducted at the University of Chicago has confirmed a decades-old theory describing the dynamics of continuous phase transitions.

The findings, published in the Nov. 4 issue of *Science*, provide the first clear demonstration of the Kibble-Zurek mechanism for a quantum phase transition in both space and time. Prof. Cheng Chin and his team of UChicago physicists observed the transition in gaseous cesium atoms at temperatures near absolute zero.

In a phase transition, matter changes its form and properties as in transitions from solid to liquid (for example, ice to water) or from liquid to gas (for example, water to steam). Those are known as first-order phase transitions.

A continuous phase transition, or second-order transition, forms defects—such as domain walls, cosmic strings and textures—where some of the matter is stuck between regions in distinct states. The Kibble-Zurek mechanism predicts how such defects and complex structures will form in space and time when a physical system goes through a continuous phase transition. Examples of continuous phase transitions include the spontaneous symmetry breaking in the early universe and, in the case of the experiment by Chin's team, a ferromagnetic phase transition in gaseous cesium atoms.

"We study phase transitions because it is one of the most fundamental questions that puzzle us," said Chin, a co-author of the paper. "What is the origin of the complex structure of the universe, how do imperfections emerge and how do identical materials develop distinct properties over time?"

Cosmologists who study the origin, evolution, structure and future of the universe also ponder phase transitions in material because it informs their understanding of what occurred throughout the history of the universe—in particular during its formation.

"What we learn from testing KZM in our system is not about the origin of the universe," Chin said. "Rather it is about how complex structure is developed through a transition. These are two different but related questions. You can ask: 'Where does snow come from?' or 'Why do snowflakes have a beautiful crystal structure?' Our investigation is more into the second question."

The findings of the experiment can be applied to many systems—such as liquid crystals, superfluid helium or even cell membranes—that go through similar continuous phase transitions. "All of them should share the same space-time scaling symmetry that we saw here," said Logan Clark, a UChicago doctoral student in physics and first author of the paper.

In the experiment, a vapor of cesium atoms was cooled using laser beams, thereby creating a quantum cesium gas. Additional laser beams were used to create an optical lattice that lined up the atoms of gas in patterns. Sound waves were used to shake the optical lattice and drive the atoms across a continuous, ferromagnetic quantum phase transition. This caused them to divide into different domains with either positive or negative momentum. The researchers found that the structure of the resulting domains was consistent with what the Kibble-Zurek mechanism would have predicted.

"The quantum gas crossing the phase transition in the optical lattice in our experiment is analogous to the entire early universe crossing a phase transition," Clark said. "Any system undergoing a continuous phase transition should share the properties we saw in our experiment."

The patterns that formed depended on how quickly the amount of shaking was ramped up, said Lei Feng, a UChicago doctoral student in physics and a co-author of the paper. "The faster the shaking was ramped up, the smaller the domains. The momentum of the atoms in different regions of the fluid was visible through the microscope, so we could see how big the domains were and count the number of defects between them."

Erich Mueller, professor of physics at Cornell University who is familiar with the research, described the findings as "a remarkable demonstration of the universality of physics."

"The same theory that is used to explain the formation of structure in the early universe also explains the formation of structure in the cold gases" used in their experiments, said Mueller, who did not participate in the study.

The work contributes to the fundamental understanding of physics, Chin said. "While cosmologists are still searching for evidence of the Kibble-Zurek mechanism, our team actually saw it in our lab in samples of atoms at extremely low temperatures.

"We are on the right track to investigate other intriguing cosmological phenomena, not only with a telescope, but also with a microscope," he concluded.

More information: L. W. Clark et al. Universal space-time scaling symmetry in the dynamics of bosons across a quantum phase transition, *Science* (2016). DOI: 10.1126/science.aaf9657

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