Quantum physics: Controlled experiment observes self-organized criticality

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Writing in *Nature*, researchers describe the first-time observation of 'self-organized criticality' in a controlled laboratory experiment. Complex systems exist in mathematics and physics, but also occur in nature and society. The concept of self-organized criticality claims that without external input, complex systems in non-equilibrium tend to develop into a critical state far away from a stable equilibrium. That way, they reinforce their own non-equilibrium.

Systems that are at first glance quite different, like the dissemination of information in social networks or the spread of fire or disease, may have similar characteristics. One example is an avalanche-like behaviour that reinforces itself instead of coming to a standstill. However, these complex systems are very difficult to study under controlled lab conditions.

For the first time, researchers from the European Centre for Quantum Sciences (CESQ) in Strasbourg, in collaboration with researchers from the universities of Cologne and Heidelberg and the California Institute of Technology, have succeeded in observing the most important features of self-organized criticality in a controlled experiment—including universal avalanche behavior.

The team worked with a gas consisting of potassium atoms, which they prepared at very low temperatures, close to absolute zero. "In this state, the gas is easier to control, which makes it more suitable for studying the fundamental quantum properties of atoms," said Professor Shannon Whitlock at the Institute of Supramolecular Science and Technology at the University of Strasbourg.

By stimulating gas atoms with lasers, the team was able to influence the interactions between these atoms. "When stimulated, the atoms can either generate new secondary stimulations or discharge spontaneously," explained Tobias Wintermantel, a doctoral researcher on Whitlock's team.

When the laser was switched on, many atoms initially escaped very quickly. Their remaining number in the gas stabilized at the same value. Also, the number of remaining particles depended on the intensity of the laser. "Comparing our lab results with a theoretical model, we saw that these two effects have the same origin," said the theoretical physicist Professor Sebastian Diehl from the University of Cologne. This was a first indication of the phenomenon of self-organized criticality.

"The experiments showed that some systems develop by themselves up to their critical point of phase transition," Diehl added. This is surprising: in a typical phase transition, like boiling water turning from liquid to gas, there is only one critical point. In boiling water, self-organized criticality would mean that the system would automatically remain in a state of suspension between liquid and gas at the critical transition point—even if the temperature was changed. So far, this concept has never been verified and tested in such a highly controllable physical system.

After the experiment, the team returned to the lab to confirm another striking feature of self-organized criticality: a self-sustaining behavior of atomic decay, similar to that of continuously replenished avalanches. Similar characteristics have already been qualitatively observed in the past in other cases—such as earthquakes or solar eruptions. "For the first time, we observed the key elements of self-organized criticality quantitatively in the lab. We were able to establish a highly controllable atomic experimental system," said Shannon Whitlock.

In further steps, the scientists now want to investigate how the quantum nature of atoms influences the self-organization mechanism. "In the long term, this might contribute to creating new quantum technologies or to solving some computation problems that are difficult for normal computers," Diehl concluded.

The phenomenon of self-organized criticality was first developed for avalanches in 1987 by physicists Per Bak, Chao Tang and Kurt Wiesenfeld. Further models by other researchers for evolution, forest fires and earthquakes followed. So far, no general conditions that trigger self-organized criticality have been identified.

More information: S. Helmrich et al. Signatures of self-organized criticality in an ultracold atomic gas, *Nature* (2020). DOI: 10.1038/s41586-019-1908-6

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