Exotic phase of matter realized on quantum processor

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Phases of matter are the basic states that matter can take—like water that can occur in a liquid or ice phase. Traditionally, these phases are defined under equilibrium conditions, where the system is stable over time. But nature allows for stranger possibilities: new phases that emerge only when a system is driven out of equilibrium. In a new study published in *Nature*, a research team shows that quantum computers offer an unparalleled way to explore those exotic states of matter.

Unlike conventional phases of matter, the so-called nonequilibrium quantum phases are defined by their dynamical and time-evolving properties—a behavior that cannot be captured by traditional equilibrium thermodynamics.

One particularly rich class of nonequilibrium states arises in Floquet systems—quantum systems that are periodically driven in time. This rhythmic driving can give rise to entirely new forms of order that cannot exist under any equilibrium conditions, revealing phenomena that are fundamentally beyond the reach of conventional phases of matter.

Using a 58 superconducting qubit quantum processor, the team from the Technical University of Munich (TUM), Princeton University, and Google Quantum AI realized a Floquet topologically ordered state, a phase that had been theoretically proposed but never before observed.

They directly imaged the characteristic directed motions at the edge and developed a novel interferometric algorithm to probe the system's underlying topological properties. This allowed them to witness the dynamical "transmutation" of exotic particles—a hallmark that has been theoretically predicted for these exotic quantum states.

Quantum computer as a laboratory

"Highly entangled nonequilibrium phases are notoriously hard to simulate with classical computers," said the first author Melissa Will, Ph.D. student at the Physics Department of the TUM School of Natural Sciences. "Our results show that quantum processors are not just computational devices—they are powerful experimental platforms for discovering and probing entirely new states of matter."

This work opens the door to a new era of quantum simulation, where quantum computers become laboratories for studying the vast and largely unexplored landscape of out-of-equilibrium quantum matter. The insights gained from these studies could have far-reaching implications, from understanding fundamental physics to designing next-generation quantum technologies.

More information: Probing Non-Equilibrium Topological Order on a Quantum Processor, *Nature* (2025). DOI: 10.1038/s41586-025-09456-3

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