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D-Wave breakthrough in quantum simulation reveals exotic phase of matter

SYNOPSIS

Summary

In volume 560 of *Nature* [1], researchers from D-Wave Systems and the Vector Institute report on a quantum simulation of a topological phase transition—subject of the 2016 Nobel Prize in Physics—in a 2-dimensional quantum magnetic system. This demonstration marks an important advance in the field: a fully-programmable annealing quantum computer can be used as an accurate programmable simulator of quantum systems at a large scale. In addition to realizing Richard Feynman's vision of a programmable quantum simulator, the methods used in this work could have broad implications in the development of novel materials.

In 1982, Richard Feynman proposed the idea of simulating the quantum physics of complex systems with a programmable quantum computer. The potential to harness the computational power of quantum mechanics for a quantum simulation of this nature has motivated the field of quantum computing for the last 35 years. Now, researchers from D-Wave Systems and the Vector Institute have demonstrated the simulation of a topological phase transition—the subject of the 2016 Nobel Prize in Physics—in a fully programmable D-Wave 2000Q annealing quantum computer. This breakthrough was recently published in *Nature*: "Observation of topological phenomena in a programmable lattice of 1,800 qubits" [1].

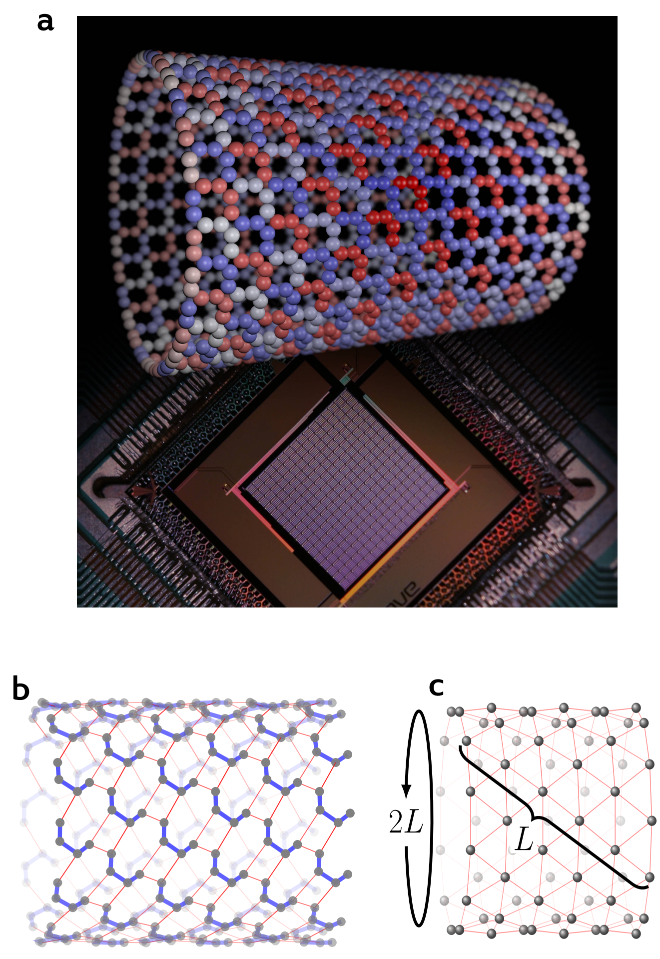

Figure 1: Programmable simulation of a quantum magnet. (**a**) The 2048-qubit D-Wave 2000Q processor is used to simulate the statistics of the square-octagonal lattice (**b**) using the theoretical framework developed for the triangular lattice (**c**).

This phenomenon is called a *Kosterlitz-Thouless* (KT) phase transition, the discovery of which led Kosterlitz and Thouless to be awarded the 2016 Nobel Prize in

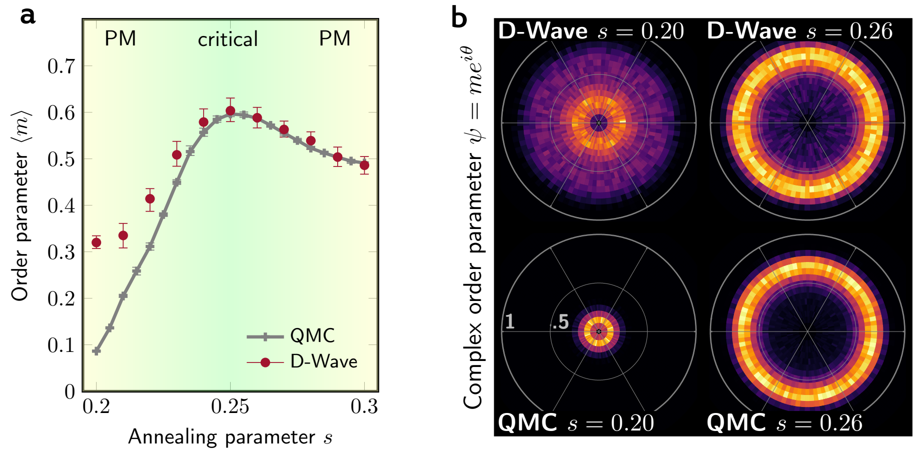

Figure 2: Simulation of order near the topological phase transition. (**a**) Order of the system—as measured by the order parameter m—increases and then decreases as the D-Wave annealing parameter s is varied from 0.2 to 0.3, representing a decrease in both quantum and thermal fluctuations. This peak in order is expected due to the location of the KT phase transition, and shows good quantitative agreement with conventional *quantum Monte Carlo* (QMC) simulations carried out on a classical processor. (**b**) The complex order parameter ψ shows rotational symmetry in both D-Wave and QMC output, as expected from previous theoretical and simulation results. At $s = 0.26$, near the peak in $\langle m \rangle$, D-Wave and QMC show the same ring in the histogram of ψ, with frequency indicated by bright colors.

Physics. This phase transition is crucial to understanding the emergence of superconductivity and superfluidity in thin films, and has been observed in many exotic physical systems, for example Bose-Einstein quasicondensates. It can be described in terms of the existence and interaction of topological defects—*vortices* and *antivortices*—and their effect on the free energy of a system with an angular degree of freedom.

In this research [1], the observation of this phenomenon is demonstrated in the *transverse-field Ising model*, the quantum model that D-Wave processors were designed to implement. The topological phenomena do not exist in the corresponding classical Ising model due to the absence of a rotational degree of freedom. The addition of quantum fluctuations completely changes the nature of the system, in an example of a phenomenon called *order by disorder* [2]. The resulting exotic phase of matter in the TFIM has been predicted by theoretical work and classical simulation, but never demonstrated experimentally. The flexibilty in programming this magnetic quantum system was crucial in realizing this phenomenon in the lattice depicted in Fig. 1b.

Strong quantitative agreement between the D-Wave processor and conventional simulations validates both the results of the quantum simulation and, more generally, D-Wave's implementation of the quantum model at large scale. Due to the existence of many symmetries, the system is extremely sensitive, and its accurate simulation involving 1800 qubits represents a breakthrough in high-fidelity control and programmability of spin interactions in quantum simulation. This simulation and the recent simulation of a 3D lattice on 2048 qubits in a D-Wave processor [3] exhibit a degree of complexity and programmability that is far beyond anything that has been demonstrated in the field of quantum computing.

References

[1] A. D. King, J. Carrasquilla, J. Raymond, I. Ozfidan, E. Andriyash, et al., "Observation of topological phenomena in a programmable lattice of 1,800 qubits," Nature **560** (2018).

[2] S. V. Isakov and R. Moessner, "Interplay of quantum and thermal fluctuations in a frustrated magnet," Physical Review B **68**, 104409 (2003).

[3] R Harris, Y Sato, A. J. Berkley, M Reis, F Altomare, et al., "Phase transitions in a programmable spin glass simulator," Science **165**, 162–165 (2018).