Study observes a phase transition in magic of a quantum system with random circuits

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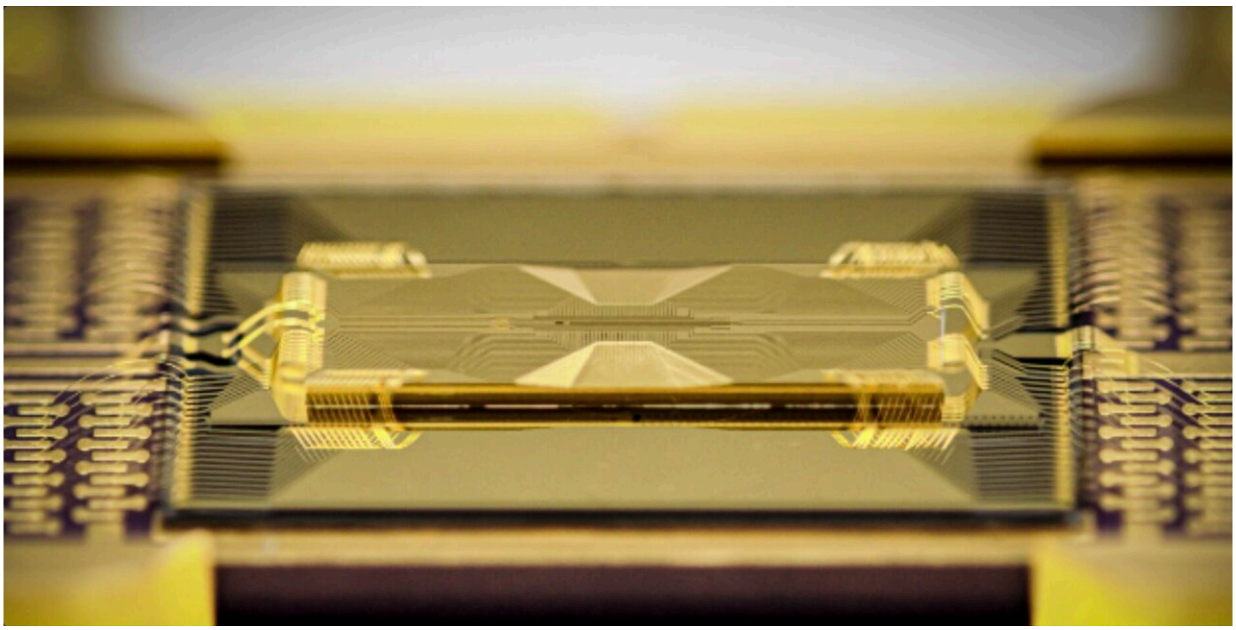


Picture of a trapped-ion quantum computer on which the experiment was conducted. Credit: IonQ

In the context of quantum mechanics and information, "magic" is a key property of quantum states that describes the extent to which they deviate from so-called stabilizer states. Stabilizer states are a class of states that can be effectively simulated on classical computers.

Magic in quantum states is crucial to the realization of universal and fault-tolerant quantum computing via simple gate operations. Gaining insight about the mechanisms behind this property could help engineers to effectively create it and leverage it, thus potentially enabling the development of better performing quantum computers.

Researchers at University of Maryland and NIST, IonQ Inc. and the Duke Quantum Center recently showed that a random stabilizer code (i.e., a code designed to protect quantum information from errors) presents vastly different behavior with regards to magic when exposed to coherent errors.

Their observations, outlined in a paper published in *Nature Physics*, could broaden the understanding of how magic states originate, which could facilitate the generation of these states in quantum computing systems.

"Even though superposition and entanglement are the terms people most often associate with quantum computers, it turns out they aren't enough to make quantum computers more powerful than classical computers," Pradeep Niroula, co-author of the paper, told Phys.org.

"To attain a quantum advantage over traditional or classical computers, you need one another ingredient called 'magic' or 'non-stabilizer-ness.' If your quantum system has no 'magic,' it can be simulated by a classical computer, making the quantum computer unnecessary. It is only when your system has a lot of magic that you go beyond what's possible with a classical computer."

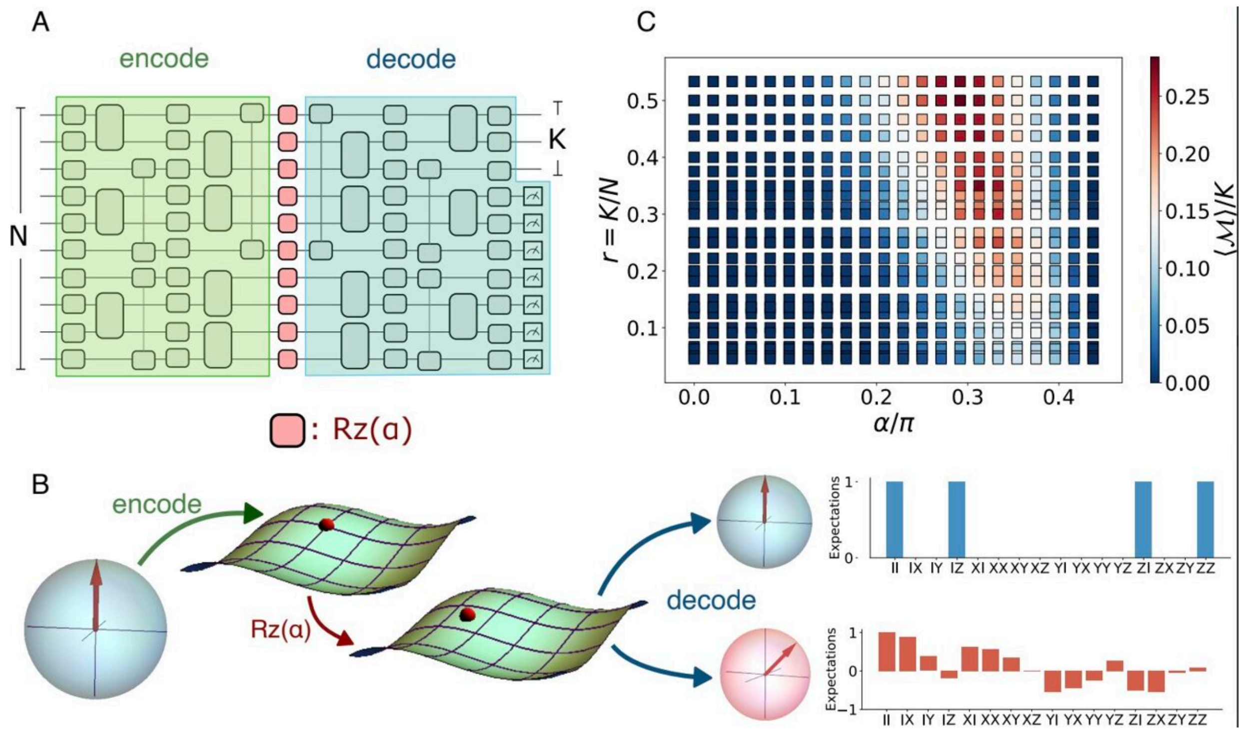
For error-resistant quantum computers, creating superpositions or entanglement between states is relatively easy. In contrast, adding magic to the state or dislocating them further from easy-to-simulate stabilizer states is expected to be highly challenging.

"In the literature of quantum information, you often encounter terms like 'magic state distillation' or 'magic state cultivation,' which refer to pretty arduous processes to create special quantum states with magic that the quantum computer can make use of," said Niroula.

"Prior to this paper, we had written a paper that observed a similar phase transition in entanglement, in which we had observed phases where measurements of a quantum system preserved or destroyed entanglement depending on how frequent they are."

While there is an extensive amount of literature focusing on the realization of entanglement in error-corrected quantum computing systems, the underpinnings of magic states remain less understood.

The main goal of the recent study by Niroula and his colleagues was to determine whether a similar phase transition as that previously observed for entanglement also exists for magic. The existence of such a transition may hint at the existence of a more general theory that is applicable to different quantum properties, including both entanglement and magic.



A) The circuit model for used in the study. Coherent error is used to tune magic on a random stabilizer code. B) A schematic illustration of how magic is created and destroyed from the circuit. The coherent errors dislocate a quantum state away from stabilizer states which are easy to represent and simulate. The final measurements sometimes destroy the injected magic, revert the states back to stabilizer states, and sometimes leave the magic intact. C) The phase diagram of magic. Credit: Niroula et al.

"A general feature of such phase transitions is that it involves two competing forces or processes," explained Niroula. "One of these creates the resource and one which destroys it—tuning the relative strength or proportion of those processes seems to reveal such transitions.

"In the case of entanglement, a quantum gate acting between two qubits tends to produce entanglement between them, whereas a measurement of one of those qubits tends to destroy the entanglement. Now if you had a quantum circuit with many gates, you can randomly add measurements in the circuit and control the spread of entanglement in the system."

Past studies focusing on entanglement in quantum circuits have established that if there are too few measurements in a quantum circuit, the entire quantum system becomes entangled. In contrast, if there are too many measurements, entanglement is suppressed and thus minimal. Moreover, if one gradually increases the density of measurements in a system, the entanglement will rapidly shift from high to almost null.

"Measurements destroy magic too, but to be able to controllably add magic to the system, you need to be able to do small rotations of the qubit," said Niroula. "So, the two competing forces here are 'how much you measure' and 'how much you rotate the qubits.' What we observed is that at a fixed rate of measurement, you can tune your rotation angle and go from a phase where you have a lot of magic to a phase where you have no magic."

As part of their study, Niroula and his colleagues first ran a series of numerical simulations, which offered a strong indication that a phase transition in magic did in fact take place. Encouraged by these findings, they then set out to test their hypothesis in an experimental setting, using real quantum circuits.

"In our experiment, we observed the signature of the phase transition even in a noisy machine," said Niroula "Our work thus uncovered a phase transition in magic.

"Earlier works have uncovered other kinds of transitions in entanglement and in charges etc. and this raises the questions: what other resources might exhibit similar transitions? Do they all belong to some universal type of transition? Are they all distinct or are they all related somehow? Also importantly, what does the presence of phase transition teach us about building noise-resilient quantum computers?"

The findings gathered by this team of researchers open new avenues for research focusing on resources in error-corrected quantum computing systems. Future studies could, for instance, explore other properties and resources that exhibit a phase transition resembling those observed for entanglement and magic.

"Magic states are important for error-correction," added Niroula. "Our work gives us some insights on when we can concentrate magic and when we can suppress it. One avenue that would be interesting to explore is to see if we can use our experiment as a 'magic state factory' where you are producing good magic states for consumption by the quantum computer.

"Currently, there is a lot of interest in the field in demonstrating the primitives or the building blocks of error-correction, and our work could be a part of that."

More information: Pradeep Niroula et al, Phase transition in magic with random quantum circuits, *Nature Physics* (2024). DOI: 10.1038/s41567-024-02637-3.