Quantum system virtually cooled to half of its actual temperature

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Physicists have developed a quantum simulation method that can "virtually cool" an experimental quantum system to a fraction of its actual temperature. The method could potentially allow access to extremely low-temperature phenomena, such as unusual forms of superconductivity, that have never been observed before. The simulation involves preparing multiple copies of the system's quantum state, interfering the states, and making measurements on each copy, which ultimately yields a simulated measurement on the same system at a lower temperature.

The team of physicists, Jordan Cotler at Stanford University and coauthors, has published a paper on the quantum virtual cooling method in a recent issue of *Physical Review X*.

As the researchers explained, the results are based on the idea that there is a strong connection between temperature and quantum entanglement.

"A modern perspective in physics is that temperature is an emergent property of quantum entanglement," Cotler told *Phys.org*. "In other words, certain patterns of quantum entanglement give rise to the familiar notion of temperature. By purposefully manipulating the pattern of entanglement in a system, we can gain access to lower temperatures. While these remarkable ideas were previously understood theoretically, we figured out how to implement them experimentally."

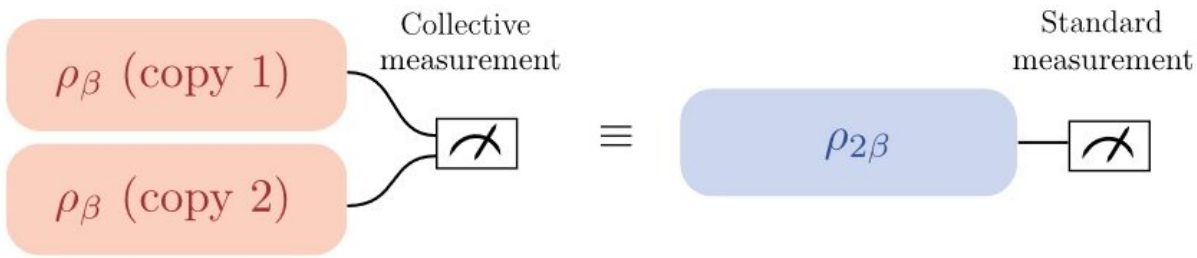
Future experimental realizations of the virtual cooling technique could enable researchers to measure temperature in seemingly impossible ways.

"We may be able to use quantum virtual cooling to 'cross' what are called finite-temperature phase transitions," Cotler said. "This seems quite bizarre—it would be like taking two glasses of liquid water, and by making a quantum measurement, you learn about the properties of solid ice. Remarkably, this seems possible in principle, but in practice, we need to use systems that are easier to control than water. Nonetheless, we still may be able to prepare a system in one phase, and use quantum virtual cooling to probe a different phase that only occurs at a lower temperature."

How it works

The virtual cooling method is designed to work on a type of system called a strongly correlated quantum many-body system. An example of such a system is a system of ultracold atoms trapped by a grid of lasers called an "optical lattice." The atoms can hop from grid point to grid point and interact with one another. Strongly correlated quantum many-body systems like ultracold trapped atoms are theoretically predicted to reveal interesting behavior at ultracold temperatures. Unfortunately, many of the predicted low-temperature phenomena have never been observed due to the difficulty of cooling to such cold temperatures.

One recently developed approach to cooling is to use a quantum simulator—a physical system consisting of atoms, photons, quantum dots, or some other physical object, which is used to model another physical system that is not as well understood. In the quantum simulator introduced in the new paper, atoms at some accessible temperature are used to model atoms at a colder, traditionally inaccessible temperature. In other words, a quantum system is being used to simulate a subset of itself at a lower temperature. Due to their quantum properties, quantum simulators can perform certain tasks like this that are out of the reach of classical computers, which cannot leverage quantum entanglement and superposition.



In the quantum virtual cooling protocol, collective measurements on two copies of a system correspond to standard measurements at half the temperature. Credit: Cotler et al. ©2019 American Physical Society

One of the key things about the new simulator is that there is no actual physical cooling involved at all. Instead, the virtual cooling is achieved by interfering many atoms, measuring those atoms, and then processing the measurement data. To demonstrate, the physicists used the method to simulate measurements of the density of atoms in what is called a "Bose-Hubbard Model," which specifies certain kinds of interactions between the atoms. The basic procedure involves preparing two or more identical copies of the many-atom quantum state in different physical locations (here, the optical lattices). Then quantum tunneling is induced between the copies, which allows atomic interference between them. Finally, the number of atoms occupying each site is measured for every lattice site, which is done by using a quantum gas microscope.

After repeating the procedure several times at the actual temperature, and then taking the average, the method gives the local density of atoms at a reduced temperature of T/n, where T is the system's actual temperature and n is the number of copies used. In the initial demonstration, the researchers used two copies, which allowed access to

the system at half of its original temperature. These experimental results closely matched theoretical predictions.

While the method theoretically allows the system to be virtually cooled all the way to its ground state, i.e., the zero-temperature state, in practice the amount of cooling is limited by scaling difficulties involved in measuring multiple copies of the system with sufficiently high precision. Still, due to the fact that no physical cooling is involved, the researchers expect that the simulation method could be used to virtually reduce the temperature of a quantum system after all physical cooling methods have been used, so it could provide additional cooling for any other method.

Cool future plans

In the future, the physicists plan to further extend the approach to extend quantum virtual cooling to measure more complicated properties. While the current set-up was designed to measure only atomic density at low temperatures, the physicists developed an alternative cooling approach to measure other properties. This approach uses qubits in a quantum circuit, similar to entanglement purification protocols.

The researchers also hope to apply quantum virtual cooling to investigate low-temperature phenomena such as d-wave superconductivity, a type of high-temperature superconductivity, which is not as well understood as low-temperature superconductivity.

"Regarding d-wave superconductivity, it would be interesting to observe it as a low-temperature phase of the Fermion-Hubbard model, which can be experimentally realized in the lab," Cotler said. "Here, 'Fermion-Hubbard model' is physics jargon for a system with specific kinds of interactions, and with constituent particles that are fermions (of which electrons are a well-known example).

"You might ask, why is this particular set of interactions interesting, and why do we care about the observation of a d-wave superconducting phase at low temperatures? There are several reasons. One is that the Fermion-Hubbard model is a nice system from a theoretical point of view, and it may yield insights into more complicated systems that we either observe in nature, or want to engineer.

"However, it is difficult to understand low-temperature superconductivity in the system—the equations are too hard, and simulating the system on a computer is nearly impossible, even if we have a supercomputer. One approach is to simulate the Fermion-Hubbard model on a quantum computer, but we do not have one yet that can do so. Instead, we can build a Fermion-Hubbard model in the lab, and explore its low-temperature properties by cooling it. In other words, we do not need a quantum computer because we are actually building the desired system in the lab. But now the problem is actually cooling down the experimental system to low enough temperatures that you can see a superconducting phase. This is currently out of reach, but it seems that quantum virtual cooling can help."

More information: Jordan Cotler et al. "Quantum Virtual Cooling." *Physical Review X*. DOI: 10.1103/PhysRevX.9.031013

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