Experiment reverses the direction of heat flow

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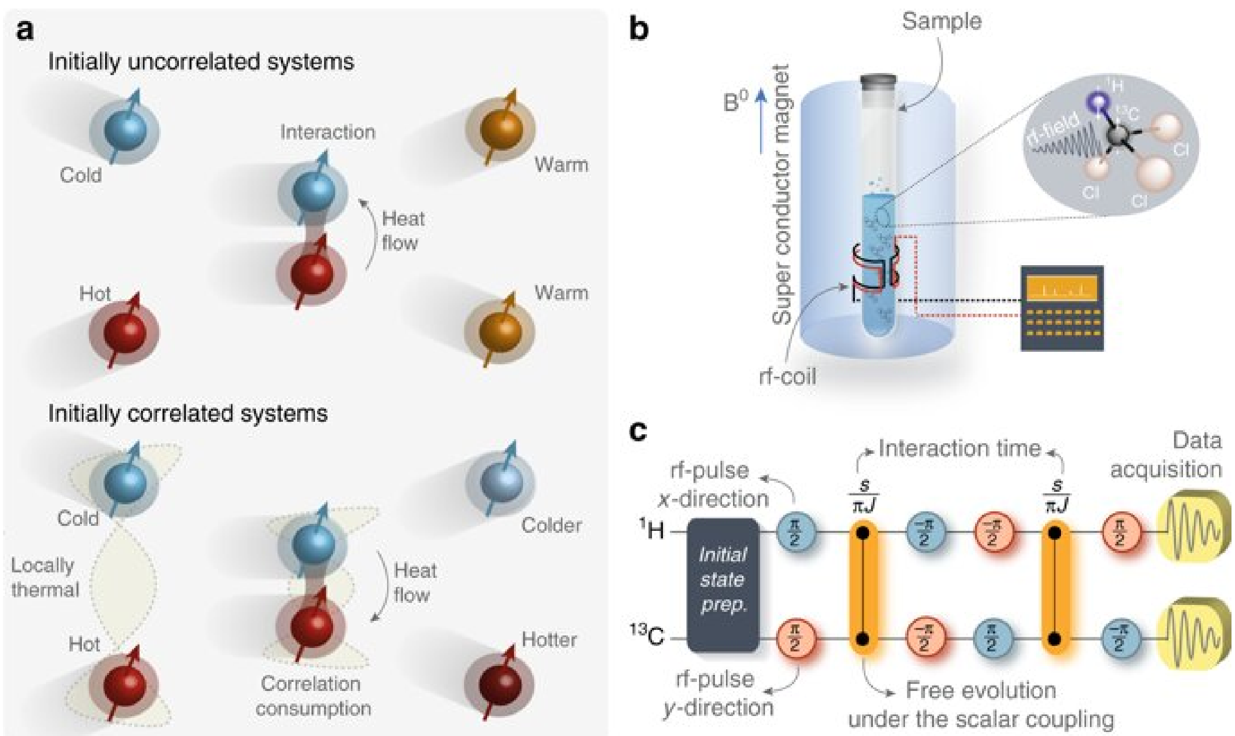

Fig. 1: Schematic of the experimental setup. a Heat flows from the hot to the cold spin (at thermal contact) when both are initially uncorrelated. This corresponds to standard thermodynamic. For initially quantum-correlated spins, heat is spontaneously transferred from the cold to the hot spin. The direction of heat flow is here reversed. b View of the magnetometer used in our NMR experiment. A superconducting magnet, producing a high-intensity magnetic field (B0) in the longitudinal direction, is immersed in a thermally shielded vessel in liquid He, surrounded by liquid N in another vacuum separated chamber. The sample is placed at the center of the magnet within the radio-frequency coil of the probe head inside a 5-mm glass tube. c Experimental pulse

sequence for the partial thermalization process. The blue (black) circle represents x (y) rotations by the indicated angle. The orange connections represents a free evolution under the scalar coupling, HHCJ=(πℏ/2)JσHzσCz, between the 1H and 13C nuclear spins during the time indicated above the symbol. We have performed 22 samplings of the interaction time τ in the interval 0 to 2.32 ms. Credit: Nature Communications, from: Reversing the direction of heat flow using quantum correlations

Heat flows from hot to cold objects. When a hot and a cold body are in thermal contact, they exchange heat energy until they reach thermal equilibrium, with the hot body cooling down and the cold body warming up. This is a natural phenomenon we experience all the time. It is explained by the second law of thermodynamics, which states that the total entropy of an isolated system always tends to increase over time until it reaches a maximum. Entropy is a quantitative measure of the disorder in a system. Isolated systems evolve spontaneously toward increasingly disordered states and lack of differentiation.

An experiment conducted by researchers at the Brazilian Center for Research in Physics (CBPF) and the Federal University of the ABC (UFABC), as well as collaborators at other institutions in Brazil and elsewhere, has shown that quantum correlations affect the way entropy is distributed among parts in thermal contact, reversing the direction of the so-called "thermodynamic arrow of time."

In other words, heat can flow spontaneously from a cold object to a hot object without the need to invest energy in the process, as is required by a domestic fridge. An article describing the experiment with theoretical considerations has just been published in *Nature Communications*.

The first author of the article, Kaonan Micadei, completed his Ph.D. under the supervision of Professor Roberto Serra and is now doing postdoctoral research in Germany. Serra, also one of the authors of the article, was supported by FAPESP via Brazil's National Institute of Science and Technology in Quantum Information. FAPESP also awarded two research grants linked to the project to another coauthor, Gabriel Teixeira Landi, a professor at the University of São Paulo's Physics Institute (IF-USP).

"Correlations can be said to represent information shared among different systems. In the macroscopic world described by classical physics, the addition of energy from outside can reverse the flow of heat in a system so that it flows from cold to hot. This is what happens in an ordinary refrigerator, for example," Serra told Agência FAPESP.

"It's possible to say that in our nanoscopic experiment, the quantum correlations produced an analogous effect to that of added energy. The direction of flow was reversed without violating the second law of thermodynamics. On the contrary, if we take into account elements of information theory in describing the transfer of heat, we find a generalized form of the second law and demonstrate the role of quantum correlations in the process."

The experiment was performed with a sample of chloroform molecules (a hydrogen atom, a carbon atom and three chlorine atoms) marked with a carbon-13 isotope. The sample was diluted in solution and studied using a nuclear magnetic resonance spectrometer, similar to the MRI scanners used in hospitals but with a much stronger magnetic field.

"We investigated temperature changes in the spins of the nuclei of the hydrogen and carbon atoms. The chlorine atoms had no material role in the experiment. We used radio frequency pulses to place the spin of each nucleus at a different temperature, one cooler, another warmer. The temperature differences were small, on the order of tens of billionths of 1 Kelvin, but we now have techniques that enable us to manipulate and measure quantum systems with extreme precision. In this case, we measured the radio frequency fluctuations produced by the atomic nuclei ," Serra said.

The researchers explored two situations: in one, the hydrogen and carbon nuclei began the process uncorrelated, and in the other, they were initially quantum-correlated.

"In the first case, with the nuclei uncorrelated, we observed heat flowing in the usual direction, from hot to cold, until both nuclei were at the same temperature. In the second, with the nuclei initially correlated, we observed heat flowing in the opposite direction, from cold to hot. The effect lasted a few thousandths of a second, until the initial correlation was consumed," Serra explained.

The most noteworthy aspect of this result is that it suggests a process of quantum refrigeration in which the addition of external energy (as is done in refrigerators and air conditioners to cool a specific environment) can be replaced by correlations, i.e., an exchange of information between objects.

Maxwell's demon

The idea that information can be used to reverse the direction of heat flow—in other words, to bring about a local decrease in entropy—arose in classical physics in the mid-nineteenth century, long before information theory was invented.

It was a thought experiment proposed in 1867 by James Clerk Maxwell (1831-1879), who, among other things, created the famous classical electromagnetism equations. In this thought experiment, which sparked a heated controversy at the time, the great Scottish physicist said that if there were a being capable of knowing the speed of each molecule of a gas and of manipulating all the molecules at the microscopic scale, this being could separate them into two recipients, placing faster-than-average molecules in one to create a hot compartment and slower-than-average molecules in the other to create a cold compartment. In this manner, a gas initially in thermal equilibrium owing to a mixture of faster and slower molecules would evolve to a differentiated state with less entropy.

Maxwell intended the thought experiment to prove that the second law of thermodynamics was merely statistical.

"The being he proposed, which was capable of intervening in the material world at the molecular or atomic scale, became known as "Maxwell's demon." It was a fiction invented by Maxwell to present his point of view. However, we're now actually able to operate at the atomic or even smaller scales, so that usual expectations are modified," Serra said.

The experiment conducted by Serra and collaborators and described in the article just published is a demonstration of this. It did not reproduce Maxwell's thought experiment, of course, but it produced an analogous result.

"When we talk about information, we're not referring to something intangible. Information requires a physical substrate, a memory. If you want to erase 1 bit of memory from a flash drive, you have to expend 10,000 times a minimum amount of energy consisting of the Boltzmann constant times the absolute temperature. This minimum of energy necessary to erase information is known as Landauer's principle. This explains why erasing information generates heat. Notebook batteries are consumed by heat more than anything else," Serra said.

What the researchers observed was that the information present in the quantum correlations can be used to perform work, in this case the transfer of heat from a colder to a hotter object, without consuming external energy.

"We can quantify the correlation of two systems by means of bits. Connections between quantum mechanics and information theory are creating what is known as quantum information science. From the practical standpoint, the effect we studied could one day be used to cool part of a quantum computer's processor," Serra said.

More information: Kaonan Micadei et al. Reversing the direction of heat flow using quantum correlations, *Nature Communications* (2019). DOI: 10.1038/s41467-019-10333-7

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