

Heated up by the cold

Cold particles transfer heat to hotter ones in a quantum experiment, thereby reversing the thermodynamic arrow of time

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An international team coordinated by Brazilian physicists has shown that a phenomenon that has never been observed in the macroscopic world can occur in a quantum system that is formed by particles of various temperatures: cold particles can spontaneously provide energy to hotter ones. A cold particle loses heat and cools down, while a hot particle gains heat and becomes hotter. This process is a reversal of the natural heat flow—known as the thermodynamic arrow of time—which normally travels from hot to cold. This surprising effect was induced by using magnetic resonance to manipulate the nuclei of carbon and hydrogen atoms in a system that was composed of liquid chloroform (CHCl_3) diluted in acetone (the three chlorine atoms that are also part of the compound molecule are not important in the experiment). For one millionth of a second, the carbon nuclei, which were colder, transferred energy to the hotter hydrogen nuclei, which heated up further. The results of the study were shared in an article on the arXiv database in November 2017 and submitted to a scientific journal for consideration.

According to the paper, a reversal of the thermodynamic arrow of time occurs only

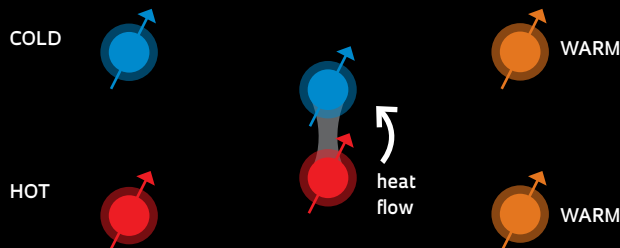


How to control the direction of energy

The initial conditions of the system determine how heat is transmitted between two particles with different temperatures

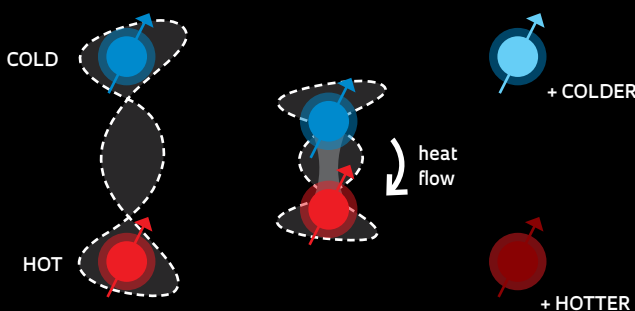
PARTICLES WITH NO QUANTUM ASSOCIATION

Under normal conditions, heat is transferred from a hot atom to a cold one. The traditional direction of heat transfer holds and both particles become warm



PARTICLES WITH A QUANTUM CORRELATION

In the new experiment, a cold atom cools down and a hot atom heats up. Heat is transferred from a cold particle to a hot one. The thermodynamic arrow of time is reversed



SOURCE MICADEI, KAONAN, ET. AL.

under the following conditions: when a quantum correlation is established between the spins (a magnetic property of the particles) of the carbon and hydrogen atoms, followed by the introduction of significant changes to the temperatures of the system components. Without this quantum correlation between the spins of the two elements, the system behaves traditionally, with the hotter particles heating up the colder ones.

QUANTUM REFRIGERATOR

Quantum correlation is similar to but weaker than the association that is known as entanglement, which is a type of bond between two or more particles. Entanglement makes it impossible to study one particle without considering the other. Although correlation is weaker than entanglement, it is still a strong enough bond that the nucleus of each chemical element shares information about its spin with that of the other. This type of quantum association is created

using radio pulses to manipulate carbon and hydrogen atoms.

The experiment can be compared to a microscopic quantum refrigerator. Everything inside the refrigerator cools down if the appliance is connected to an external source of electricity. “For a cold body to heat a hot one, the system needs to be supplied with extra energy,” explains physicist Roberto Serra, from the Federal University of ABC (UFABC), who is one of the researchers involved in the study, conducted by the Brazilian National Institute for Quantum Science and Technology (INCT-IQ). In the experiment, which was performed at the Brazilian Physics Research Center (CBPF) laboratory in Rio de Janeiro, additional energy was provided by applying various magnetic fields to the chloroform molecules. Thus, it was possible to make the nuclei of the hydrogen atoms hotter than those of the carbon atoms. The system was prepared in a way that causes heat to flow from cold particles to hot ones.

The results of the study could disturb the delicate boundary between classical thermodynamics and quantum mechanics. According to the second law of thermodynamics, entropy and disorder tend to increase over time in the macroscopic world; in nature, energy dissipates. This is why hot coffee does not spontaneously heat up in a cup—it cools down. However, at the limit of what can be considered atoms and electrons, strange phenomena occur: the direction of the heat flow can reverse and the entropy of the system can decline, thereby creating the impression that time has reversed. “Our research falls under the scope of thermodynamics of small quantum systems,” says Kaonan Micadei, who is the lead author of the article and a PhD student at UFABC.

Classical thermodynamics does not consider the existence of initial associations—such as those that are created by quantum correlation or entanglement—between particles such as atoms and electrons. However, this is an important issue that could help explain how microsystems dissipate energy. “The experiment is fundamental to understanding thermodynamic phenomena that are linked to the development of quantum computing,” comments CBPF’s Ivan Santos Oliveira, who coauthored the study. “The experiment helps us verify the laws of physics,” says theoretical physicist David Jennings, from Imperial College London, UK, who did not participate in the study.

Processing information generates heat. It is estimated that 20–30% of all the electricity that is produced in the world is used to cool computers. Limiting the dissipation of energy in quantum machines is one of the primary motivations of those who participated in the experiment. “Creating a quantum refrigerator is a necessary step toward producing a more complex quantum device,” says Serra. ■

Project

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Scientific article

Micadei, K. et al. Reversing the thermodynamic arrow of time using quantum correlations. Available on [arXiv](#).