Experiments detect entropy production in mesoscopic quantum systems

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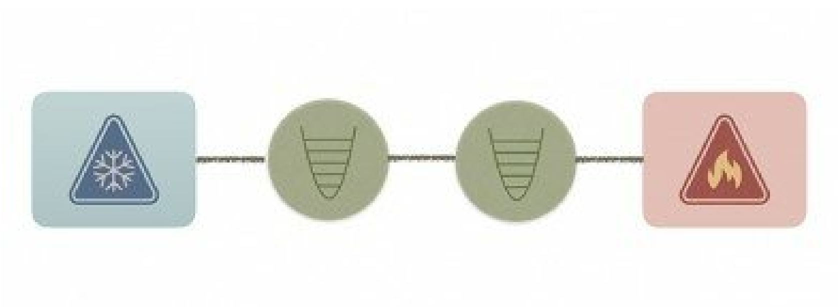

Illustration of a stationary state that is obtained when two quantum harmonic oscillators (in green) are coupled to two heat baths at different temperatures. In this case, a current of heat will flow from the hotter to the colder reservoir, demonstrating irreversible behavior. The experiments described in the study were selected because they conceptually resembled this simplified situation. Credit: Gabriel Teixeira Landi

The production of entropy, which means increasing the degree of disorder in a system, is an inexorable tendency in the macroscopic world owing to the second law of thermodynamics. This makes the processes described by classical physics irreversible and, by extension, imposes a direction on the flow of time. However, the tendency does not necessarily apply in the microscopic world, which is governed by quantum mechanics. The laws of quantum physics are reversible in time, so in the microscopic world, there is no preferential direction to the flow of phenomena.

One of the most important aims of contemporary scientific research is knowing exactly where the transition occurs from the quantum world to the classical world and why it occurs—in other words, finding out what makes the production of entropy predominate. This aim explains the current interest in studying mesoscopic systems, which are not as small as individual atoms but nevertheless display well-defined quantum behavior.

A new experimental study by researchers from Brazil and elsewhere offers an important contribution to this field. An article about it has recently been published in *Physical Review Letters*.

"We studied two systems: a Bose-Einstein condensate with 100,000 atoms confined in a cavity and an optomechanical cavity that confines light between two mirrors," Gabriel Teixeira Landi, a professor at the University of São Paulo's Physics Institute (IF-USP), told.

Landi was one of the scientists responsible for developing a theoretical model correlating the production of entropy with measurable quantities for both experiments. The research is supported by São Paulo Research Foundation—FAPESP. The Bose-Einstein condensate was studied at the Swiss Federal Institute of Technology (ETH Zurich), and the cavity optomechanics device was studied at the University of Vienna in Austria.

Often called the "fifth state of matter" (the other four being solids, liquids, gases and plasma), Bose-Einstein condensates are obtained when a group of atoms is cooled almost to absolute zero. Under these conditions, the particles no longer have the free energy to move relative to each other, and some of them enter the same quantum states, becoming indistinguishable from one another. The atoms then obey so-called Bose-Einstein statistics, which usually apply to identical particles. In a Bose-Einstein condensate, the entire group of atoms behaves as a single particle.

An optomechanical cavity is basically a light trap. In this particular case, one of the mirrors consisted of a nanometric membrane capable of vibrating mechanically. Thus, the experiment involved interactions between light and mechanical vibration. In both systems, there were two reservoirs, one hot and the other cold, so that heat could flow from one to the other.

"Both situations displayed signatures of something irreversible and therefore demonstrated an increase in entropy. Furthermore, they exhibited irreversibility as a consequence of quantum effects," Landi said. "The experiments permitted classical effects to be clearly distinguished from quantum fluctuations."

The main difficulty in this line of research is that entropy production cannot be measured directly. In the experiments in question, therefore, the scientists had to construct a theoretical relationship between entropy production and other phenomena that signal irreversibility and are directly measurable. In both cases, they chose to measure the photons leaking from the cavities, having deliberately used semitransparent mirrors to allow some light to escape.

They measured the average number of photons inside the cavities and the mechanical variations in the case of the vibrating mirror.

"Quantum fluctuations contributed to an increase in irreversibility in both experiments," Landi said. "This was a counterintuitive discovery. It's not necessarily something that can be generalized. It happened in these two cases, but it may not be valid in others. I see these two experiments as an initial effort to rethink entropy on this kind of platform. They open the door to further experimentation with a smaller number of rubidium atoms or even smaller optomechanical cavities, for example."

Information loss and disorder

In a recent theoretical study, Landi showed how classical fluctuations (vibrations of atoms and molecules, producing thermal energy) and quantum fluctuations could occur simultaneously, without necessarily contributing to the same results. That study was a forerunner of the two new experiments.

"Both the condensate and the light-confining cavity were mesoscopic phenomena. However, unlike other mesoscopic phenomena, they had perfectly preserved quantum properties thanks to shielding from the environment. They, therefore, provided controlled situations in which entropy production competition between classical and quantum phenomena could be very clearly observed," Landi said.

"Entropy can be interpreted in various ways. If we think in terms of information, an increase in entropy means a loss of information. From the standpoint of thermodynamics, entropy measures the degree of disorder. The greater the entropy, the greater the disorder in the system. By combining these two views, we can obtain a more comprehensive understanding of the phenomenon."

Both the Bose-Einstein condensate and the optomechanical cavity are examples of so-called "quantum simulation platforms." These platforms enable scientists to circumvent a major obstacle to the advancement of knowledge because there are important systems in nature for which descriptive models exist but for which predictions cannot be made owing to calculation difficulties. The most famous example is high-temperature superconductivity. No one understands how certain materials can behave as superconductors at the boiling point of liquid nitrogen (approximately -196° C).

The new platforms provide quantum devices that can simulate these systems. However, they do so in a controlled manner, eliminate all complicating factors, and focus only on the simplest phenomena of interest. "This idea of quantum simulation has caught on significantly in recent years. Simulations range from important molecules in medicine to key structures in cosmology," Landi said.

More information: M. Brunelli et al, Experimental Determination of Irreversible Entropy Production in out-of-Equilibrium Mesoscopic Quantum Systems, *Physical Review Letters* (2018). DOI: 10.1103/PhysRevLett.121.160604

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