

Viewpoint

Nuclear Spin Points out Arrow of Time

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*Entropy production, a quantity associated with the emergence of the arrow of time, has been successfully measured in a microscopic quantum system.*Subject Areas: **Statistical Physics, Quantum Physics****A Viewpoint on:****Irreversibility and the Arrow of Time in a Quenched Quantum System**

T. B. Batalhão, A. M. Souza, R. S. Sarthour, I. S. Oliveira, M. Paternostro, E. Lutz, and R. M. Serra

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Compared to many weird-sounding concepts in physics, the idea that time has a preferred direction seems downright obvious. After all, a broken glass won't reassemble into one piece. But the origin of the arrow of time isn't at all obvious to physicists. This is because the physical laws that describe microscopic systems are reversible: rewind the clock and two colliding particles will go back from where they came. Where then does irreversibility come from? Is there some undiscovered source of irreversibility at the microscopic scale? Or does it emerge when crossing some microscopic-macroscopic boundary? A new contribution to this already active dialogue [1–3] comes from Roberto Serra at the Federal University of ABC, Brazil, and colleagues [4]. They have, for the first time, experimentally measured the entropy production in a microscopic, quantum system: a nuclear spin (Fig. 1). A positive entropy production is a proxy for the arrow of time, and having measured it, the authors open the door to studying time's arrow on the quantum scale.

What does it mean to measure time's arrow? Formally, the existence of an arrow of time is dictated by the second law of thermodynamics, which says the entropy of a closed system can only increase [1]. And although experimentalists cannot rewind the movie of a thermodynamic transformation, they can measure by *how much* this rewinding is impossible. This is quantified by the entropy production, which is zero if the movie can be rewound and positive if—as is most often the case—it cannot.

This quantity, and hence time's arrow, is what Serra and colleagues set out to measure in a quantum system. To do so, they followed a general method that involves three ingredients: an external operator, who controls a system that interacts in an uncontrolled way with a thermal bath. (The same elements are found in a heat engine, with the calorific fluid serving as the system.) A trans-

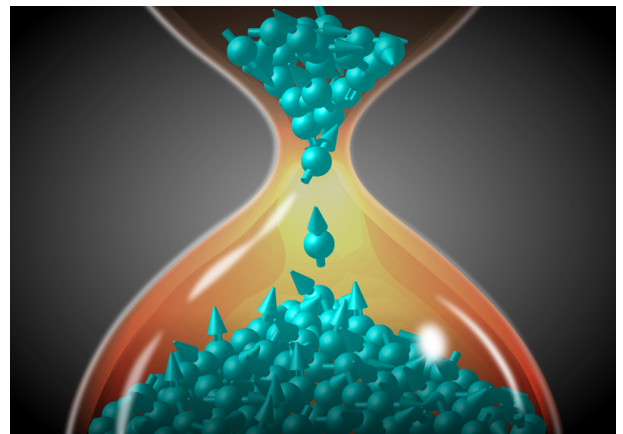


FIG. 1: Serra and colleagues detected the arrow of time in a nuclear spin—the smallest quantum system in which the emergence of time's direction has been observed. (APS/Alan Stonebraker)

formation corresponds to the operator using a protocol to drive the system for a period of time. For instance, the operator might change one of the system's parameters over time using an external field, and then reverse this protocol by rewinding the field's evolution.

Intuitively, entropy production will be zero if, after completion of the forward and backward protocols, the system returns to its starting point. This can occur in at least two situations. The first is a system isolated from any bath and fully controlled by the operator. This "trivial" case shows the critical role of the bath in the emergence of the arrow of time: the bath randomizes the dynamics and without it, processes are reversible. But there is a second case in which a transformation is reversible in the presence of a bath. For this to happen, the system must be driven sufficiently slowly that, at

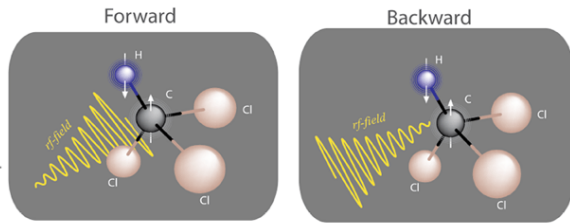


FIG. 2: The quantum system studied by Serra and colleagues is the nuclear spin of a carbon-13 atom (grey sphere) on a chloroform molecule. (Left) They applied a radio-frequency magnetic field pulse (yellow) and then (right) applied a pulse whose shape was flipped in time compared to the first pulse—a process a bit like running a quantum-scale movie forwards and backwards. They show the average entropy produced after the forward and backward pulses are applied is always positive, indicating an arrow of time for the quantum spin system. (T. B. Batalhão *et al.* [6])

any time in the protocol, the system is allowed to reach equilibrium with the bath. This type of adiabatic process corresponds to the most efficient way of operating heat engines, such as the celebrated Carnot engine [5].

A transformation can, however, be performed so fast that the system is driven out of equilibrium. This leads to a positive entropy production and a definite arrow of time. Departure from equilibrium can happen if the system is driven faster than the time it needs to relax to equilibrium with the bath (classical adiabaticity breaking) or if it is driven faster than its typical transition frequency (quantum adiabaticity breaking). It is the latter regime that Serra and colleagues have experimentally investigated.

To do so, they utilized nuclear magnetic resonance (NMR), which is one of the best experimental methods to date for studying thermodynamics on the quantum scale. The system they studied is an ensemble of spin-1/2 particles, where each spin is from a carbon-13 nucleus in a chloroform molecule in a liquid. One measurement on this ensemble corresponds to repeating a measurement many times on a single spin. The external field of their forward protocol is a time-varying magnetic field pulse; the backward protocol is simply this same pulse flipped in time (Fig. 2). They imposed thermal equilibrium before running each protocol by applying carefully chosen sequences of magnetic pulses. Because of this thermalizing step, work done on the spin or by the spin is stochastic (random). And it is quantized because of the spin’s quantum nature.

They measured entropy production in two independent ways. First, they used NMR tomography to determine the distribution of quantum states occupied by the carbon-13 spins before and after applying the forward and reverse protocols. The relative entropy between these two distributions quantifies how different they are

and exactly corresponds to the mean entropy production. Second, they used an interferometric technique [6] to detect changes in the spins’ energy distribution during the forward protocol and during the backward protocol. These changing distributions correspond to the (quantum) probability of work being done on or by the system. The log of the ratio of these two probabilities is, according to a theoretical relation [7], equal to the entropy production. In this way, the authors were able to extract the average entropy production and compare it to the directly measured value, finding very good agreement. Such a comparison provides a check on the idea that entropy production is a physical quantity and not just a theoretical definition.

Serra and colleagues have demonstrated that it is possible to perform controlled thermodynamic experiments in the quantum regime. This ability opens the door to a better understanding of the origin and consequences of the arrow of time. It will, for example, allow researchers to explore fundamental questions in the areas of quantum information and thermodynamics. In particular, how does irreversibility relate to the loss of quantum information or quantum coherence [8]? Could quantum thermodynamics lead to new criteria with which to distinguish different interpretations of quantum mechanics? How is irreversibility quantitatively related to the energetic cost of quantum computation [9]? The exciting conversation between thermodynamics and quantum physics continues.

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About the Author



Alexia Auffèves is a researcher working at the Néel Institute of Grenoble, France. Under the supervision of Serge Haroche, she completed her Ph.D. in experimental physics at the Laboratoire Kastler Brossel, where she prepared Schrödinger-cat states of light. In 2005, she assumed a position at the CNRS in the field of quantum optics with semiconductors. Since then, she has shifted her focus to theory. Her current fields of interest include quantum optics, quantum open systems, the foundations of quantum physics and quantum thermodynamics.