Viewpoint

Nuclear Spin Points out Arrow of Time

Alexia Auffèves

Université Grenoble Alpes, F-38000 Grenoble, France and
CNRS, Institut Néel, "Nanophysique et semiconducteurs" group, F-38000 Grenoble, France

Published November 02, 2015

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

Physical Review Letters 115, 190601 2015 – Published November 2, 2015

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 transformation 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...
ward and reverse protocols. The relative entropy between terms is used to determine the distribution of quantum states occupied by 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.

This research is published in Physical Review Letters.

References

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.

DOI: 10.1103/Physics.8.106
URL: http://link.aps.org/doi/10.1103/Physics.8.106