Physicists extend stochastic thermodynamics deeper into quantum territory

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Thermodynamic laws that describe heat and energy are being extended to the quantum scale. Source: Pexels. Photograph by Paweł Kadysz

Physicists have extended one of the most prominent fluctuation theorems of classical stochastic thermodynamics, the Jarzynski equality, to quantum field theory. As quantum field theory is considered to be the most fundamental theory in physics, the results allow the knowledge of stochastic thermodynamics to be applied, for the first time, across the full range of energy and length scales.

The physicists, Anthony Bartolotta, a graduate student at Caltech, and Sebastian Deffner, Physics Professor at the University of Maryland Baltimore County, have written a paper on the Jarzynski equality for quantum field theories that will be published in an upcoming issue of *Physical Review X*.

The work address one of the biggest challenges in fundamental physics, which is to determine how the laws of classical thermodynamics can be extended to the quantum scale. Understanding work and heat flow at the level of subatomic particles would benefit a wide range of areas, from designing nanoscale materials to understanding the evolution of the early universe.

As Bartolotta and Deffner explain in their paper, in contrast to the large leaps made in the "microscopic theories" of classical and quantum mechanics during the past century, the development of thermodynamics has been rather stagnant over that time.

Although thermodynamics was originally developed to describe the relation between energy and work, the theory traditionally applies only to systems that change infinitely slowly. In 1997, physicist Christopher Jarzynski at the University of Maryland College Park introduced a way to extend thermodynamics to systems in which heat and energy transfer processes occur at any rate. The fluctuation theorems, the most prominent of which is now called the Jarzynski equality, have made it possible to understand the thermodynamics of a wider range of smaller, yet still classical, systems.

"Thermodynamics is a phenomenological theory to describe the average behavior of heat and work," Deffner told *Phys.org*. "Originally designed to improve big, stinky heat engines, it was not capable of describing small systems and systems that operate far from equilibrium. The Jarzynski equality dramatically broadened the scope of thermodynamics and laid the groundwork for stochastic thermodynamics, which is a new and very active branch of research."

Stochastic thermodynamics deals with classical thermodynamic concepts such as work, heat, and entropy, but on the level of fluctuating trajectories of atoms and molecules. This more detailed picture is particularly important for understanding thermodynamics in small-scale systems, which is also the realm of various emerging applications.

It wasn't for another decade, however, until the Jarzynski equality and other fluctuation theorems were extended to the quantum scale, at least up to a point. In 2007, researchers determined how quantum effects modify the usual interpretation of work. However, many questions still remain and overall, the area of quantum stochastic thermodynamics is still incomplete. Against this backdrop, the results of the new study represent a significant advance.

"Now, in 2018 we have taken the next big step forward," Deffner said. "We have generalized stochastic thermodynamics to quantum field theories (QFT). In a certain sense we have extended stochastic thermodynamics to its ultimate range of validity, since QFT is designed to be the most fundamental theory in physics."

One of the keys to the achievement was to develop a completely novel graph theoretic approach, which allowed the researchers to classify and combine the Feynman diagrams used to describe particle behavior in a new way. More specifically, the approach makes it possible to precisely calculate infinite sums of all the possible permutations (or arrangements) of disconnected subdiagrams describing the particle trajectories.

"The quantity we were interested in, the work, is different than the quantities usually calculated by particle theorists and thus required a different approach," Bartolotta said.

The physicists expect that the results will allow other scientists to apply the fluctuation theorems to a wide variety of problems at the forefront of physics, such as in particle physics, cosmology, and condensed matter physics. This includes studying things like quantum engines, the thermodynamic properties of graphene, and the quark gluon plasma produced in heavy ion colliders—some of the most extreme conditions found in nature.

In the future, the physicists plan to generalize their approach to a wider variety of quantum field theories, which will open up even further possibilities.

More information: Anthony Bartolotta and Sebastian Deffner. "Jarzynski Equality for Driven Quantum Field Theories." *Physical Review X*. DOI: 10.1103/PhysRevX.8.011033. Also at arXiv:1710.00829 [cond-mat.stat-mech]