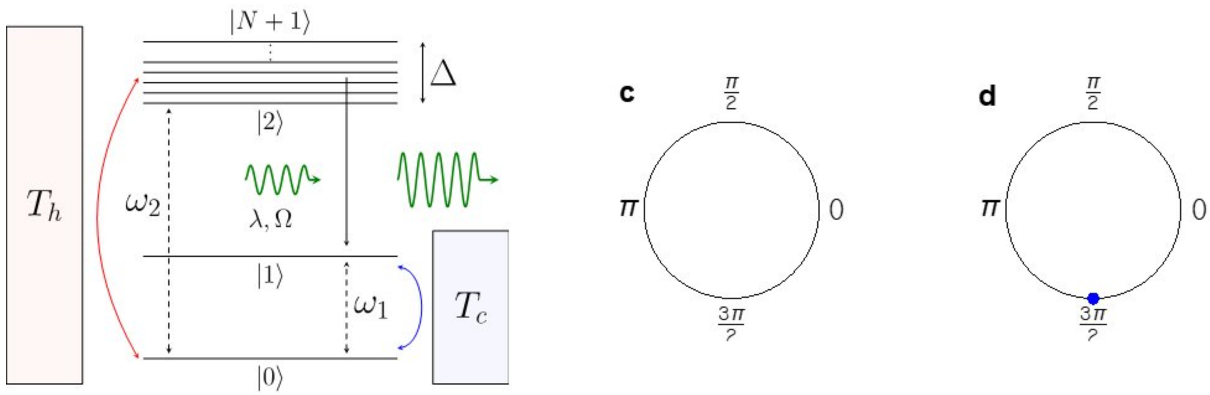
Unveiling synchronization preferences of quantum thermal machines

July 18 2023



(a) Schematic diagram of the quantum thermal machine considered. The red and blue rectangles represent hot and cold baths, the horizontal lines represent the quantum energy levels of the working medium, and the green wavy lines represent laser light. Contrasting synchronization behavior of the system when it acts as an engine (b) and refrigerator (c). In the "chaotic" engine regime the phases are distributed uniformly between [0,2π] whereas in the "calm" refrigerator regime the phases are all localized at 3π/2. Credit: Institute for Basic Science

Researchers from the Center of Theoretical Physics of Complex Systems within the Institute for Basic Science (PCS-IBS) made an important discovery that describes the relationship between synchronization and thermodynamics in quantum systems.

The question of how order arises from disorder has captivated humanity for centuries. One fascinating example of such emergence is synchronization, where multiple oscillators initialized randomly could end up oscillating in harmony. Synchronization exists in our everyday lives—for example, the sound of clapping hands or the simultaneous flashing of fireflies.

Remarkably, scientists have discovered many instances of synchronization in diverse natural and artificial phenomena, including in very small systems governed by quantum mechanics.

At the same time, the study of synchronization must also consider the second law of thermodynamics which only allows the total disorder of the universe to increase. This means that for a spontaneous emergence of order-like synchronization to occur, there has to be a cost of increasing disorder somewhere else (e.g., a wasteful heat in the surrounding environment). Yet, despite these intriguing connections, the precise relationship between synchronization and thermodynamics remains a mystery.

To unravel the underlying connection between synchronization and thermodynamics in the quantum regime, PCS-IBS researchers investigated a novel quantum thermal machine that exhibits synchronization. This machine is capable of acting as a quantum heat engine or as a quantum refrigerator. The study is published in the journal *Physical Review Letters*.

As a heat engine, it transforms heat flow from hot to cold baths to amplify the intensity of laser light. Conversely, as a refrigerator, it uses energy from laser light to maintain the temperature of the cold bath. Importantly, this machine is able to undergo synchronization simultaneously while performing its task due to its continuous interaction with the laser.

Curiously, the researchers found that as they scaled up the machine, multiple synchronizing actors started to arise within the machine. The synchronization behavior of the machine was not solely influenced by its interaction with lasers but also by the interplay between its various components.

These distinct synchronization actors could both cooperate and compete, much like two individuals jumping on a trampoline—for example, let's call them Jack and Jill. Cooperation arises when both Jack and Jill adjust their jumping rhythm in harmony, reaching their highest and lowest points simultaneously. Conversely, competition occurs when Jack attempts to match Jill's rhythm while Jill deliberately does the opposite, such as aiming to be at the lowest point when Jack reaches his highest.

According to the corresponding author, Dr. Juzar Thingna, "This is the first example in which synchronizing quantum systems are shown to cooperate and compete, opening a path to a richer synchronization landscape like quantum chimeras."

Intriguingly, the cooperation and competition between different synchronization mechanisms are intimately related to the thermodynamic functionality of the machine. Cooperation manifests in the case of the refrigerator, i.e., they have a preference for a system that synchronizes in harmony, like a peaceful orchestra. On the other hand, competition arises in the case of heat engines, as their components thrive in the middle of a crazy party and use all the chaos to perform at their best.

These findings are important because not only do they shed light on the fundamental relation between synchronization and thermodynamics, but they also give us new ideas for designing quantum technologies and relate the abstract notion of synchronization to the performance of quantum devices.

In other words, improving our understanding of how synchronization works in quantum machines, will allow us to make better devices that work coherently together. This could lead to more efficient and powerful quantum machines that will one day ignite the quantum revolution.

More information: Taufiq Murtadho et al, Cooperation and Competition in Synchronous Open Quantum Systems, *Physical Review Letters* (2023). DOI: 10.1103/PhysRevLett.131.030401

Provided by Institute for Basic Science