Divulga UAB
Revista de difusió de la recerca de la Universitat Autònoma de Barcelona

05/10/2026

How fast can nature reach equilibrium?



A new study from the Grup d'Informació Quàntica (GIQ) at the Department of Physics of the UAB, together with collaborators from Wien and Geneva, have shown that quantum mechanics establishes a fundamental limit to how fast physical systems can reach thermal equilibrium.

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Thermalization is the process by which physical systems reach thermal equilibrium, and it is one of the most universal phenomena in nature. If a glass of milk is placed in a refrigerator and left there long enough, it will eventually reach the same temperature as its surroundings, regardless of its initial microscopic state, including its temperature, molecular arrangement, or countless other details.

This remarkable tendency of physical systems to forget microscopic details and converge towards simple equilibrium states has fascinated physicists for centuries. Although a glass of milk contains an astronomical number of particles, its equilibrium state can be described by only a handful of macroscopic quantities, such as temperature, pressure, and volume. This extraordinary simplification lies at the heart of thermodynamics, one of the most successful theories in science.
But what determines how long a system takes to reach equilibrium? Is there a fundamental limit to how quickly thermalization can occur?

In recent work, Martí Perarnau-Llobet and John Calsamiglia from the Grup d'Informació

Quàntica (GIQ) at the Universitat Autònoma de Barcelona, together with collaborators from the Institute for Quantum Optics and Quantum Information (IQOQI Vienna), TU Wien, and the University of Geneva, have shown that the answer is yes.

Quantum mechanics is famous for enabling exotic phenomena such as entanglement and quantum computation. Less widely appreciated is that it also constrains what physical processes can achieve. The researchers show that these constraints imply a fundamental limit on the speed of thermalization.
The relevant timescale is the so-called Planckian dissipation time, $\tau_{Pl} = \hbar/(k_B T)$, where $\hbar$ is the reduced Planck constant and $k_B T$ sets the thermal energy scale. The hotter a system, the faster it can, in principle, reach equilibrium.
At room temperature τ_{Pl} is about 25 femtoseconds, comparable to the fastest molecular motions. In ultracold atomic gases, only a few nanokelvin above absolute zero, it stretches to several milliseconds and can be measured directly in experiments.

For more than two decades, physicists have suspected τ_{Pl} sets a universal minimum timescale for thermalization, based on observations in materials such as high-temperature superconductors. Yet proving such a bound has remained surprisingly difficult. If the Hamiltonian of a system, the mathematical object that determines its microscopic dynamics, is known in advance, one can prepare a particular thermal state arbitrarily quickly. Simply asking how fast a thermal state can be prepared is therefore not sufficient to establish a universal limit.

The new work approaches the problem from a different perspective. The researchers consider a hypothetical thermalization machine that must obey quantum mechanics and successfully thermalize systems governed by different possible Hamiltonians. This reflects the universality of thermalization observed in everyday life: a coffee placed in the refrigerator eventually reaches equilibrium regardless of the precise way its molecules interact with one another.

Using tools from quantum metrology, the science of precisely estimating physical parameters, the researchers show that no such machine can determine which Hamiltonian governs a system arbitrarily quickly. This limitation directly translates into a minimum thermalization time, essentially equal to half the Planckian timescale.

The result shows that the Planckian bound is not a peculiarity of specific materials or theoretical models. Instead, it emerges as a fundamental consequence of quantum mechanics itself. Nature may be remarkably efficient at erasing microscopic details and driving systems towards equilibrium, but even this process cannot occur arbitrarily fast.

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References

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