FLOQUET PRETHERMALIZATION

The quick drive to pseudo-equilibrium

A clever application of nuclear magnetic resonance techniques offers a glimpse at a quantum system driven at high frequency, resulting in Floquet prethermalization — a quasi-steady state that persists for a very long time.

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Applying a time-dependent perturbation to a quantum system can drastically modify its dynamics. A good example is the use of external oscillating fields to probe the energy levels of atoms and molecules that are otherwise inaccessible with stationary Hamiltonians. The possibilities under non-equilibrium conditions are very exciting: kicking a system before it has had a chance to thermalize can bring about the appearance of new phases of matter[1–4] and induce phenomena that are either non-existent or difficult to achieve at equilibrium[5,6]. Now, writing in *Nature Physics*, Pai Peng and colleagues report that they have observed one such phenomenon — known as Floquet prethermalization — by exploiting the power of nuclear magnetic resonance (NMR) techniques in a system made of nuclear spins[7].

Prethermalization refers to a pseudo-equilibrium phase characterized by a non-thermal quasi-steady state. It can emerge when a quantum system is subjected to a small time-independent perturbation. This prethermal metastable state may persist for a very long time before the perturbation finally takes the system to its true thermal equilibrium. Alternatively, prethermalization can also be achieved by periodically driving the system at a high frequency. This second scenario is known as 'Floquet prethermalization' in allusion to the Floquet formalism usually employed to describe periodically driven systems.

If the quantum system is driven at a low frequency, its evolution operator follows random matrix theory and its eigenstates are reminiscent of random pure states. In other words, the system quickly reaches thermal equilibrium at infinite temperature. The opposite happens under high-frequency driving, where prethermal states may be achieved and persist for exponentially long times[5,6]. At first sight, this may seem counterintuitive, as one might expect a system that gets kicked more frequently to absorb more energy. But the following mathematical explanation helps to dismiss this deceptive intuition.

Suppose the periodic driving leads to an evolution that alternates nearly instantaneously between two non-commuting and time-independent Hamiltonians H_1 and H_2, each acting during the time interval τ, so that a cycle is completed after the total driving period 2τ, as sketched in Fig. 1a. The Floquet propagator after n cycles is then given by $(e^{-iH_2\tau}e^{-iH_1\tau})^n$. If the system is driven at high frequency, such that the period τ is small, the evolution will be approximately governed by the time-independent average Hamiltonian given by the sum of H_1 and H_2. In this case, a quantity conserved by this effective Hamiltonian experiences a prethermal regime with an exponentially long lifetime, as illustrated in Fig. 1b. In contrast, if the driving frequency is low, and τ is large, the higher-order terms of the average Hamiltonian cannot be neglected and the evolution operator becomes similar to that for random matrices.

Peng and collaborators[7] effectively engineered a system capable of mimicking the evolution described in Fig. 1a. Their experiment was conducted at room temperature on a natural crystal known as fluorapatite. By taking advantage of NMR techniques, they were able to remove interactions between different spin species, so that the remaining effective couplings were those between the spin-1/2 ^{19}F nuclei, which interact through dipolar interactions. These spins are arranged in linear chains of average length in excess of 50 sites, as sketched in Fig. 1c. The intrachain interactions are much stronger than the interchain interactions, meaning that the system behaves like independent chains of spin-1/2 particles for a substantial amount of time.

The group then applied a designed sequence of short radiofrequency fields that collectively rotated the spins. The resulting system evolved as depicted in Fig. 1a with dynamics controlled by one of two Hamiltonians on each interval τ. They were able to vary the spacing between the pulses, which allowed them to analyse the dynamics under different driving frequencies.

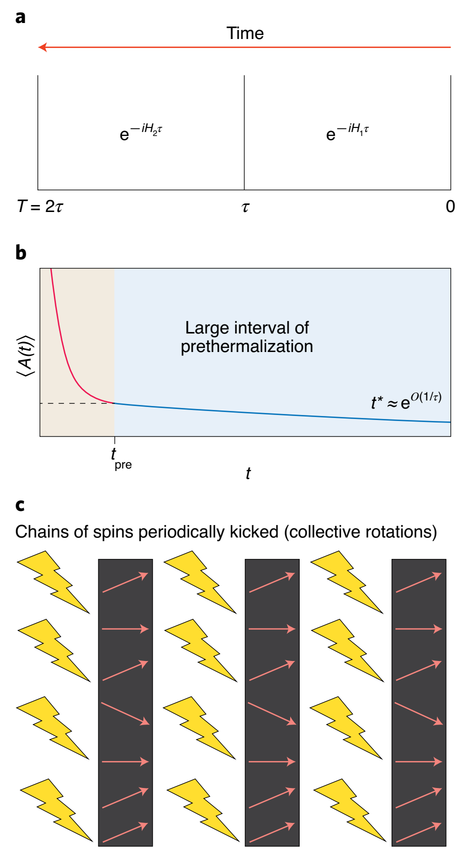

Fig. 1 | Floquet driving of spin chains and the prethermalization behaviour of observable *A*. **a**, The periodic drive leads to an evolution that switches between two non-commuting Hamiltonians, H_1 and H_2, each one active on an interval τ. **b**, When the period of the cycle, $T = 2\tau$, is small, the expectation value $\langle A(t)\rangle$ of a quantity A that commutes with the prethermal Hamiltonian $H_{pre} \approx H_1 + H_2$ reaches a prethermal regime at $t_{pre} \approx 1/|H_{pre}|$ that lasts for an exponentially long time, until thermalization is finally achieved at a time exponentially large on the order of $1/\tau$, that is, $t^* \approx e^{O(1/\tau)}$. **c**, The experimental system[7] consists of ensembles of long spin-1/2 chains. A sequence of collective rotations of spins generates an evolution given by repetitions of the cycle illustrated in **a**.

The prethermal Hamiltonian of the experiment by Peng and collaborators was not exactly the effective average

Hamiltonian written above, but it was very close to it. As the two Hamiltonians nearly commute, the group selected the average Hamiltonian as one of their observables and measured it stroboscopically at the end of each cycle. They verified that the observable indeed reached a metastable state when the driving frequency was large, confirming the onset of the prethermal phase.

Owing to the long relaxation time of the sample, Peng and colleagues were able to treat the system as nearly isolated. And owing to exquisite control over errors introduced by pulse imperfections and higher-order terms in the engineered Hamiltonians, the authors were also capable of resolving the subsequent exponentially slow heating of the system up to the fully thermalized state at infinite temperature.

The prethermal energy was not the only quasi-conserved quantity that emerged. The experiment revealed an additional quantity, similar to the dipolar Hamiltonian, which was conserved even beyond the regime described by the average Hamiltonian. This suggests the existence of Floquet phases with no static counterpart, opening up a new direction in the search for robust non-equilibrium phases of matter.

The work by Peng and colleagues illustrates the potential of NMR experiments, which have recently gained traction in the realm of condensed-matter physics. In NMR imaging and spectroscopy, the use of external fields to manipulate and modify a given Hamiltonian dates back to the 1950s. The idea later acquired a new dimension in quantum information theory, where NMR decoupling techniques became useful for reducing environmental noise and engineering Hamiltonians. But the experiment by Peng and collaborators belongs to yet another wave, in which the problems of condensed-matter physics and statistical mechanics are being investigated with NMR platforms. So far, we have seen progress in many-body localization[8], static prethermalization[9] and now in achieving long-lived Floquet phases of matter. We cannot help but wonder enthusiastically what lies ahead. ❐

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