An inexpensive crystal makes a fine quantum time machine

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The laws of classical mechanics are time reversible. A movie of a particle, or even a few colliding particles, looks equally realistic when played forward or backward. An ensemble of many particles, on the other hand, is characterized by a parameter, entropy, that always increases with time. As the system progresses toward thermal equilibrium, it loses all memory of its initial nonequilibrium state.

Classical physics ultimately derives from quantum physics, because all real-world classical systems are composed of quantum systems. Classical many-body ensembles thermalize, so quantum ones seemingly must do the same. But the nature of quantum time evolution—described mathematically by a so-called unitary operator—means that quantum information can never be created or destroyed and quantum systems can never lose their memory of their previous states.

To resolve that apparent paradox and gain a deeper understanding of what "thermalization" means in the quantum world, researchers seek to study how information propagates across a nonequilibrium quantum system. To do that, they need methods, whether theoretical or experimental, to link the single-body and many-body scales with enough detail and control to coherently track the evolution of quantum states and enough interacting particles to exhibit meaningful thermodynamics. That's hard.

Now MIT's Paola Cappellaro and colleagues are finding that a way forward might lie in a surprisingly simple experimental setup: an inexpensive natural crystal—bought from a jewelry vendor on eBay for $10—and an ordinary NMR machine.[1,2] The crystalline material, called fluorapatite, has long been recognized as a useful model of one-dimensional spin chains.[3] Its fluorine atoms, depicted in red in figure 1, are arranged into long, well-separated columns that are interrupted only by rare crystal defects.

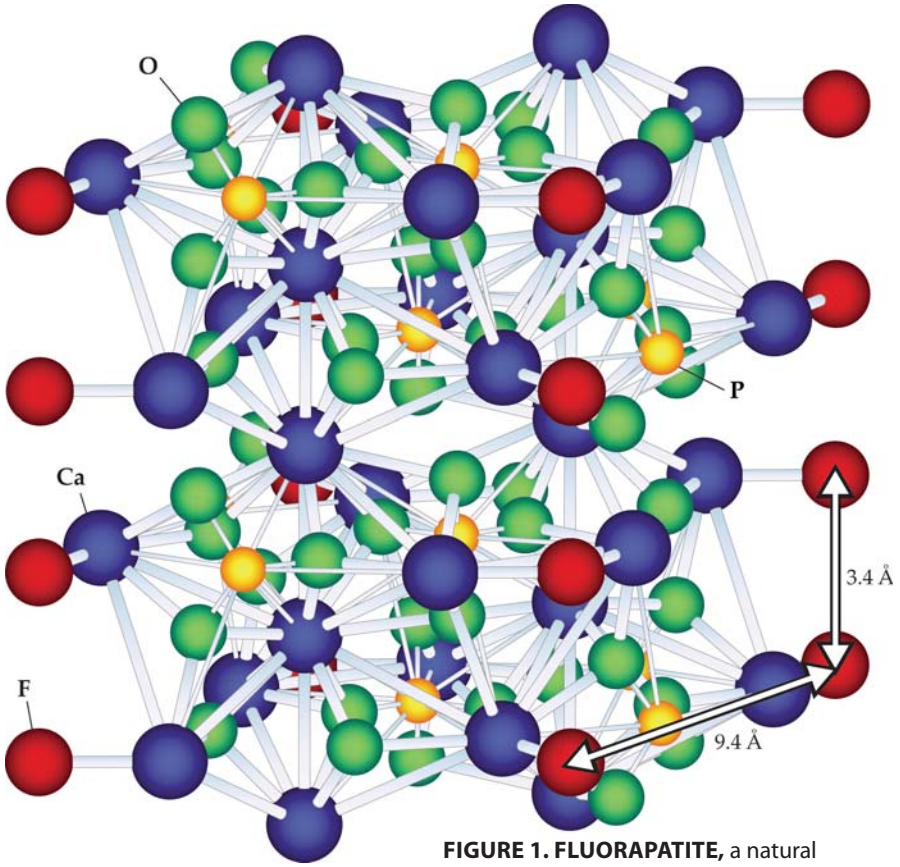

FIGURE 1. FLUORAPATITE, a natural material sometimes used as an inexpensive gemstone, is a compound of calcium (blue), phosphorus (yellow), oxygen (green), and fluorine (red). Because the distance between F atoms in the horizontal plane is nearly three times the distance between nearest-neighbor F atoms in the vertical direction, the F atoms thus approximate an ensemble of one-dimensional spin chains. (Adapted from W. Zhang et al., *Phys. Rev. A* **80**, 052323, 2009.)

Fluorine's only stable isotope is the spin-½, NMR-active ^{19}F. Using the techniques of solid-state NMR (see the article by Clare Grey and Robert Tycko, PHYSICS TODAY, September 2009, page 44), Cappellaro and colleagues are able not only to manipulate and probe the ^{19}F spins but also to tinker with the effective Hamiltonian that describes how the spins evolve. One of the things they can do, importantly, is create opposite-signed versions of the same Hamiltonian, which effectively propagates the system forward and backward in time.

The ability to rewind time lets the researchers construct an experimental measure, based on a so-called out-of-time-order (OTO) commutator, of how thoroughly their spin system has explored its space of available quantum states. Roughly speaking, a system in thermal equilibrium is equally likely to be found anywhere in that space, and a system out of equilibrium is not. By measuring OTO commutators, Cappellaro and colleagues can see how swiftly and completely their spin chains approach equilibrium—and get a glimpse of the peculiar ways in which quantum systems sometimes fail to thermalize.

Out of order

An OTO commutator is similar to the familiar commutators used in quantum mechanics to quantify the compatibility, or lack thereof, of pairs of observables. For example, a particle's position x and

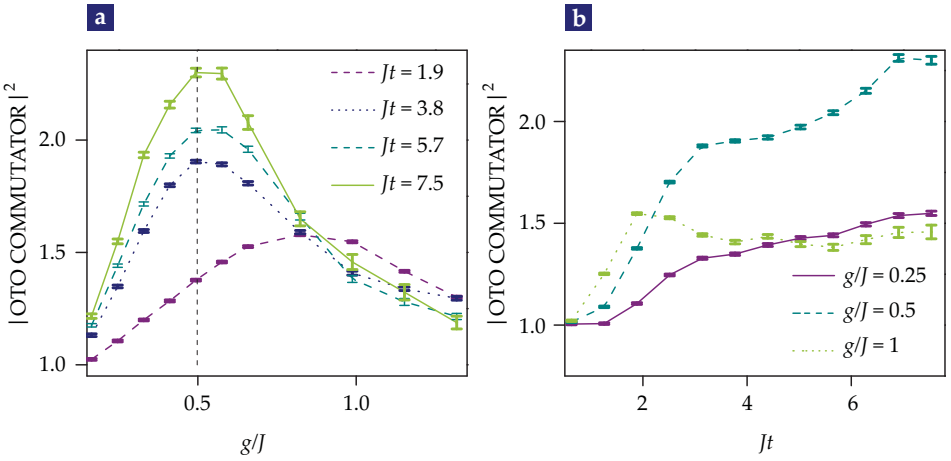

FIGURE 2. PRETHERMALIZATION DYNAMICS emerges in the fluorapatite spin system when the effective magnetic field g is relatively large compared with the spin–spin interaction strength J. **(a)** When g/J is 0.5 or less, the magnitude of an out-of-time-order (OTO) commutator grows steadily with time t, the hallmark of quantum thermalization. For larger values of g/J, the OTO commutator stops growing when the system reaches a prethermal steady state. **(b)** Here, the data are plotted as a function of t rather than g. (Adapted from ref. 2.)

momentum p aren't simultaneously measurable; if both are measured, the order of the measurements matters. Mathematically speaking, the operators representing those quantities don't commute: $px - xp$ is nonzero.

The "out of time order" part comes from considering the two operators at different times—say, x at time 0 and p at time t. The OTO commutator asks, Does measuring $x(0)$ then $p(t)$ give the same results as measuring $p(t)$ then $x(0)$? That is, does $p(t)x(0) - x(0)p(t)$ equal zero?

From a theoretical perspective, there's nothing paradoxical about the idea of making a later measurement first and an earlier measurement second. One need only write down a factor of $e^{iHt/\hbar}$ in between their two operators, where H is the system's Hamiltonian, to represent the rewinding of time. (Forward-propagating time, in contrast, is represented by $e^{-iHt/\hbar}$.)

Experimentally, it's also possible, at least in principle, to turn back the clock on any quantum system. A quantum state has a unique backward trajectory in time, just as it has a unique forward trajectory, and an ably chosen combination of measurements can extract information about what that trajectory is. Despite their apparent oddity, OTO commutators can make both mathematical and physical sense.

OTO commutators are especially useful as probes of how information spreads throughout a quantum system—as, for example, an initially localized spin excitation diffuses along a chain of interacting spins. At first, the states of spins at opposite ends of the chain are compatible observables—measuring one has no effect on the other. But as time goes by and each spin's influence spreads across the system, distant spins become progressively more entangled, and their OTO commutator steadily increases with increasing t.

At least, that's what's expected of a system that approaches thermal equilibrium. There are at least two ways in which a quantum system might fail to fully explore its space of available states, even at effectively infinite temperature where energy barriers between states no longer matter. First, there's many-body localization, a cousin to the long-studied and simpler Anderson localization (see the article by Ad Lagendijk, Bart van Tiggelen, and Diederik Wiersma, PHYSICS TODAY, August 2009, page 24). In a many-body localized system, disorder in the Hamiltonian—for example, a spatially varying magnetic field acting on the particles in a spin chain—traps quantum information in localized regions and prevents distant spins from becoming entangled.

Second, there's prethermalization, in which a system's conserved (or quasi-conserved) quantities confine it to only a portion of its state space. In that case, the system quickly approaches a partially thermalized—or prethermal—steady state, which spans as much of the quantum state space as is possible subject to the conserved quantities. Full thermalization happens on a much longer time scale, if it happens at all.

Those exceptions to quantum thermalization can be used to construct extraordinary quantum systems, called time

crystals, that enter perfectly periodic orbits in state space rather than chaotically exploring the whole space. (See the article by Norman Yao and Chetan Nayak, PHYSICS TODAY, September 2018, page 40.) Researchers want to understand more about how many-body localization and prethermalization work. What effects do they produce, and under what conditions? Does anything interesting happen at the boundary between thermalizing and nonthermalizing systems? Are nonthermalizing systems as rare in the quantum world as they are in the classical world, or are they common?

Into the unknown

Although OTO commutators have been considered theoretically for half a century, the first experimental steps toward using them to study quantum thermalization were taken only in 2017, when two groups independently measured OTO commutators for relatively simple systems. Xinhua Peng, of the University of Science and Technology of China, and her colleagues used NMR measurements on a molecular system containing four spins.[4] And Ana Maria Rey and colleagues at JILA looked at a lattice of trapped ions whose spins rotate collectively.[5] Both groups observed straightforward dynamics that agreed with simulations. Cappellaro and colleagues' fluorapatite experiments, on long chains of fluorine spins, are the first to study quantum thermalization in a system complicated enough that it's hard to simulate with high fidelity.

All three groups use similar techniques to turn back the clock on their quantum systems. With a repeating sequence of RF or microwave pulses, they apply a time-dependent perturbation to the system in order to modify the system's natural Hamiltonian. Carefully chosen pulse sequences can tune Hamiltonian parameters such as the spin–spin interaction strength, turn on or off an effective magnetic field, and even invert the sign of the whole Hamiltonian to make the system effectively propagate backward in time.

Because all the fluorine atoms in fluorapatite reside in identical chemical environments, they all resonate at the same frequency, so NMR can't address their spins individually. That means that Cappellaro and colleagues can neither prepare nor detect site-specific spin states, and they can't make different pairs of adjacent spins interact with different strengths. Rather, they're limited to looking at collective observables such as the total magnetization in some direction. Fortunately, an OTO commutator between two collective observables works just as well for quantifying the system's exploration of quantum state space as an OTO commutator between the states of distant spins.

An important parameter the researchers can tune is the strength of the interaction between the fluorine spins and the nearby phosphorus spins. The phosphorus spins are randomly oriented, so their net effect is a random, spatially varying magnetic field acting on the F-atom spin chain. The random field is just the kind of disorder to produce many-body localization, as Cappellaro and colleagues observed last year.[1] When they increased the strength of the disorder by applying an RF pulse sequence that enhanced the fluorine–phosphorus coupling, they saw that spin correlations progressively failed to spread along the fluorine chain.

In their latest work, they've turned to prethermalization.[2] They turn off the disorder in their effective Hamiltonian, and they replace it with a uniform effective magnetic field of strength g. When g is large enough relative to the fluorine–fluorine spin interaction strength J, the field makes the dominant contribution to the Hamiltonian, and the total energy is approximately proportional to the magnetization in the field direction. Because the magnetization is approximately conserved, the system can no longer efficiently explore the whole state space, which encompasses states with different total magnetization. The quasiconserved quantity at high g should tip the system into the prethermal regime, as should be evident from OTO commutator measurements.

And the hallmark of the prethermal regime is just what they see, as shown in figure 2. The two panels depict the same data plotted in different ways. Each data point corresponds to a single measurement of an OTO commutator for a particular value of the effective field g and the time interval t. The low-field, rapidly thermalizing regime is exemplified by $g/J = 0.5$, shown by the vertical dashed line in figure 2a and the blue-green data in figure 2b; the OTO commutator swiftly grows with increasing t. On the

other hand, in the high-field, prethermal regime, exemplified by $g/J = 1$, the OTO commutator grows for a short time and then stops, signaling that the system has reached a prethermal steady state.

Fluorapatite, therefore, has been shown to be a powerful model quantum many-body system that can be tuned into and out of the prethermalization and many-body localization regimes. Moreover, Cappellaro and colleagues have demonstrated that the OTO commutator can serve as an experimental probe of thermalization dynamics that may be applicable to other physical systems—including, perhaps, ones so complicated that theorists have no idea what to expect.

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An odd fluid shows its inner workings

Viscous forces drive waves along a two-dimensional fluid's free surface.

In a conventional fluid such as water, molecules tumble in random directions. Researchers in the fields of active matter, fluid dynamics, materials science, and condensed matter have long contemplated what would happen if the molecules' rotations were instead coordinated, creating a so-called chiral fluid.

Parity, or mirror, symmetry restricts the ways in which conventional fluids can respond to applied forces. A flow caused by an external force in a conventional fluid can break mirror symmetry and lead to phenomena such as instabilities and vortices. In nature, most fluids exist in a perturbed, symmetry-broken state. In contrast, a chiral fluid built of spinning particles breaks mirror symmetry without the need for an externally forced flow. Theorists posit that a chiral fluid could intrinsically possess new properties not found in conventional fluids.

Materials such as two-dimensional electron gases and liquid crystals break mirror symmetry. And collections of spinning magnets and rotating bacteria are examples of systems that exhibit some of the large-scale patterns, such as unidirectional edge currents, predicted for a chiral fluid.

Creating a liquid that behaves in similar ways has remained an elusive goal until now. Researchers in William Irvine's lab at the University of Chicago have for the first time developed a chiral fluid in the lab and identified the mechanisms that give rise to its unusual surface flows.[1]

One-way waves

The Irvine group's chiral fluid is a 2D colloidal suspension. To create the chiral fluid, graduate students Vishal Soni and Ephraim Bililign and postdoc Sofia Magkiriadou, all at the University of Chicago, suspended billions of 1.6 μm hematite cubes, made by Soni and collaborator Stefano Sacanna (New York University), in a thin layer of water atop a glass slide. A rotating magnetic field caused the cubes to spin simultaneously in the same direction. After a few minutes of spinning, the colloidal magnets, shown in figure 1, attracted each other enough to behave as a liquid.

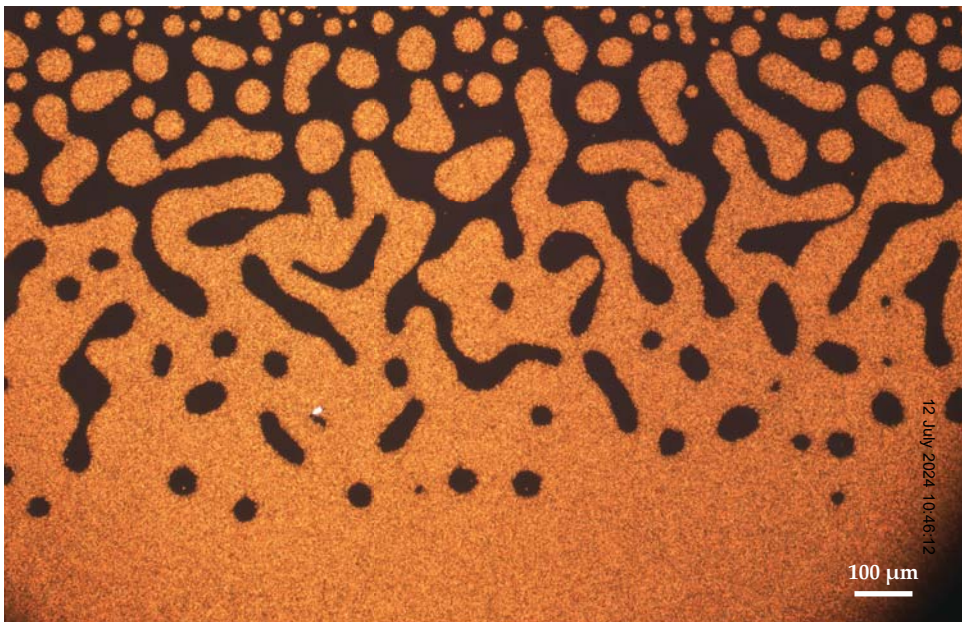

FIGURE 1. AN OPTICAL MICROGRAPH shows a bulk fluid of colloidal magnets (orange). After a few minutes of spinning, the particles attracted each other and formed a cohesive material. (Adapted from ref. 1.)

The material displayed several types of macroscale behavior reminiscent of a conventional fluid with positive surface tension. Nearby clusters of spinning particles merged into larger droplets. When the glass slide was tilted, the droplets bumped up against a hard edge and spread out, like raindrops on a windshield joining and then flattening when they hit the frame. When an obstacle was removed from the bulk, the voids quickly filled, like bubbles collapsing.

The material also displayed patterns not typical of a conventional fluid but expected for a chiral fluid. With no external stimulation beyond the rotating field, clockwise currents formed at the interface between the clockwise-spinning colloids and the suspending liquid. Such edge currents follow from the symmetry breaking caused by particles' active rotation in the chiral fluid.[2] Instantaneous velocity profiles of a chiral fluid droplet showed that the edge current extended to a finite depth δ into the bulk. For the 100-μm-diameter droplet shown in figure 2, the current depth was 4.5 μm.

High-resolution videos of the 2D