least two of them must be nonzero, but it's not even known which one is the largest. In the so-called normal hierarchy—in which m_3, the mass of the state made up mostly of the muon and tau flavor states, is largest—the half-lives of neutrinoless decays would be roughly 10^{29} yr. In the inverted hierarchy, in which m_3 is the smallest, they're around 10^{27} yr. They're both far beyond the reach of current Xe-based detectors but could be observable by future ones.

As WIMP experiments become more sensitive, they could also double as real-time neutrino detectors in a uniquely low-energy regime. Right now, neutrinos from the Sun are just one of several sources of background—they appear as the orange curve in figure 2—but that can change as the detectors grow and other background components are comparatively reduced. Whereas water-based neutrino detectors, such as Super-Kamiokande, can see only those rare solar neutrinos produced by beta decay of boron-8 (see PHYSICS TODAY, December 2015, page 16), a Xe-based detector could provide a complementary view by detecting the far more numerous neutrinos from proton–proton fusion.

The XENON1T detector has already been shut down, and the XENON researchers are getting ready for their next upgrade, XENONnT, with 8 tons of Xe. It will be joined in the next few years by two other new detectors: LZ (for LUX–Zeplin, a merging of the Large Underground Xenon and the Zoned Proportional Scintillation in Liquid Noble Gases experiments) in South Dakota and PandaX-4T (Particle and Astrophysical Xenon detector) in Sichuan, China. The main goal is still to look for WIMPs, but it's now clear that that's not all the detectors are capable of. "Maybe we'll stumble upon something totally unexpected along the way," says Wittweg, "as so often happens in physics."

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A raft of soap bubbles remembers its past

Information can be encoded in, and extracted from, the ostensibly random arrangement of a soft glass.

Amorphous materials, such as glasses and gels, are characterized by a plethora of available configurations that look much the same. With a single low-energy ordered configuration off limits—either because it doesn't exist or because it's kinetically inaccessible—their energy landscapes are rugged labyrinths with many local minima, each corresponding to a specific disordered arrangement of the constituent particles.

That disorder can carry more information than meets the eye. Amorphous solids are eternally out of equilibrium, and a hallmark of nonequilibrium thermodynamics is that systems retain information about their history. (For more about how that history dependence is exploited in glass physics, see the article by Ludovic Berthier and Mark Ediger, PHYSICS TODAY, January 2016, page 40.) Put another way, two configurations that are virtually identical in their bulk properties (such as density and energy) and microscopic measures (such as autocorrelation functions) are nevertheless distinct states, and they may be distinguishable by properties we don't yet know how to measure.

Now Srimayee Mukherji, her master's thesis adviser Rajesh Ganapathy, and their colleagues Ajay Sood and Neelima Kandula at the Jawaharlal Nehru Centre for Advanced Scientific Research in Bangalore, India, have shown experimentally[1] that they can manipulate the information contained in a raft of soap bubbles like the one shown in figure 1.

The bubbles' size distribution is chosen so that they can't settle into a configuration of crystalline order, and the system behaves like a soft glass. The researchers "train" the raft by applying shear oscillations at a particular strain amplitude γ_t. Shearing rearranges the bubbles in a way that seems to be random: No visible feature distinguishes a trained raft from an untrained one. Nevertheless, a suitable readout protocol can extract the value of γ_t several minutes or more after training. A single raft can even hold simultaneous memories of two different γ_t values—and in principle, more than that.

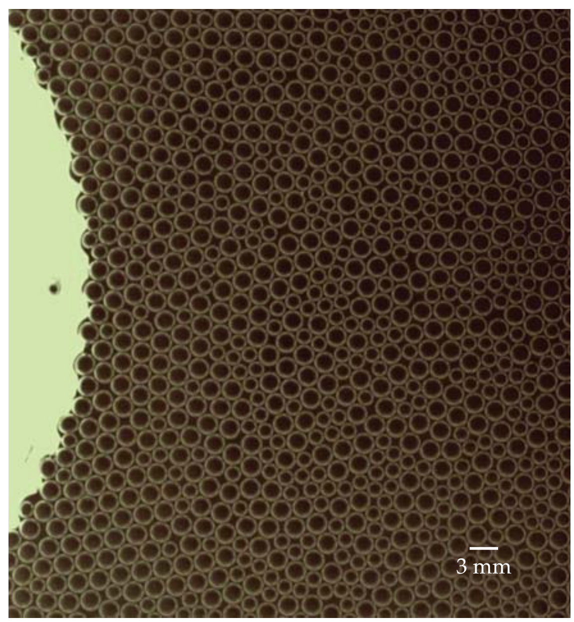

FIGURE 1. A BUBBLE RAFT in a Couette cell. Although the disordered arrangement of bubbles appears random, it contains information about shearing amplitudes the raft has experienced. (Courtesy of Rajesh Ganapathy.)

The memory appears to be related to the bubble raft's yielding transition. Below a shear strain $\gamma_y = 0.06$, the raft behaves like an elastic solid; for larger strains, it deforms plastically. Surprisingly, the system can remember γ_t values both greater and less than γ_y, and the closer γ_t is to γ_y, the stronger the memory signature. Although yielding behav-

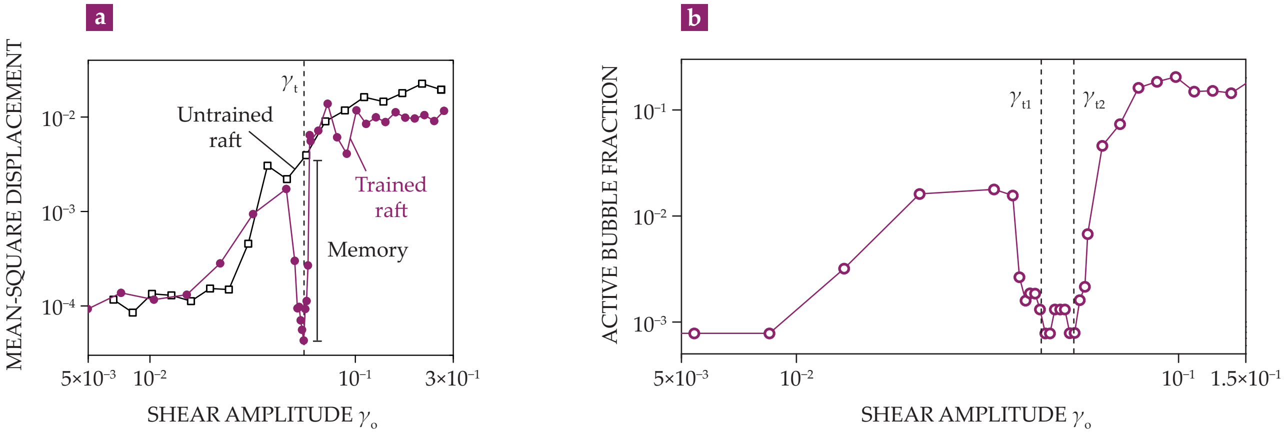

FIGURE 2. SIGNATURES OF MEMORY in a bubble raft's response to an increasing shear strain amplitude γ_o. **(a)** When a raft is trained by shear oscillations at $\gamma_t = 0.056$, its response (purple) looks much like that of an untrained raft (black) except for a sharp drop at γ_t. **(b)** A raft trained at two amplitudes, $\gamma_{t1} = 0.042$ and $\gamma_{t2} = 0.053$, remembers them both. (Adapted from ref. 1.)

ior is found in many everyday materials, including whipped cream and solid cooking fats (see the Quick Study by Braulio Macias Rodriguez and Alejandro Marangoni, PHYSICS TODAY, January 2018, page 70), a rigorous theory of the transition is still elusive.[2] The connection between memory and yielding has the potential to shed new light on both.

Raft training

Many condensed-matter systems exhibit memory of past conditions. In addition to all the systems used and explored for practical data storage, material memories include any system that exhibits hysteresis or is sensitive to its preparation pathway. Recent years have seen a push for a more unified view of memory phenomena, to draw connections among the behaviors of disparate systems.[3] For example, dilute colloidal suspensions under cyclic shear can remember their history in a way that bears a striking resemblance to how charge-density-wave solids remember the durations of electrical pulses (for an overview of the latter, see the article by Robert Thorne, PHYSICS TODAY, May 1996, page 42).

Five years ago, at about the same time as the experiments on sheared suspensions, a trio of theorists predicted a similar yet distinct memory behavior in sheared amorphous solids.[4] Ganapathy and his group, who had experience working with granular and colloidal systems under shear, decided to take a look. They opted to use bubble rafts rather than a system of solid particles, because the bubbles interact frictionlessly. The challenge was keeping the bubbles from bursting or coalescing during the experiment.

It's been known for a century that soap bubbles made by the right recipe can be kept stable for hours or longer; James Dewar, among his other achievements, was a pioneer of soap film research (see the article by Robert Soulen, PHYSICS TODAY, March 1996, page 32). But the bubbles in that early work weren't subjected to constant shearing and squeezing. Says Ganapathy, "We tried a whole bunch of different surfactants before we converged on one that worked"—a mixture of toy bubble solution and sodium stearate bar soap.

The bubbles are placed in a Couette cell, the 4-cm-wide annular region between an inner disk (visible at the left of figure 1) and an outer ring (not shown). Rotating the disk alternately clockwise and counterclockwise applies an oscillating shear strain whose amplitude the raft remembers. A typical training protocol comprises 17 oscillations with period 10 seconds.

The researchers characterized the response to shear oscillations by filming the raft and calculating how far each bubble moved from the beginning of one cycle to the beginning of the next. For training amplitudes γ_t much less than γ_y, the mean-square bubble displacement was always essentially zero: The raft deformed elastically, and each bubble returned to its original position. For larger values of γ_t, but still less than γ_y, the first few shear cycles rearranged some bubbles, but after that, the raft settled into a state of purely elastic deformation. For $\gamma_t > \gamma_y$, the mean-square displacement started high and decreased but plateaued at a nonzero value: No matter how much the raft is trained in the plastic regime, each new cycle always rearranges some bubbles.

In the readout protocol, the researchers applied a series of shear oscillations of gradually increasing amplitude γ_o, and they measured the raft response in terms of either the mean-square displacement or the fraction of bubbles displaced by more than a tenth of their diameters. Attempting to read an untrained raft (black data in figure 2a) shows nothing out of the ordinary: The deformation starts out elastic at low amplitudes and becomes gradually more plastic as γ_o is increased.

The readout of a trained raft (purple data in figure 2a) looks similar, except at γ_t, where the mean-square displacement drops by up to two orders of magnitude. Figure 2b shows the readout of a raft trained on two amplitudes, γ_{t1} and γ_{t2}; it simultaneously remembers them both. For each raft, to better measure the sharpness of the memory signals, the researchers scanned γ_o more slowly in the vicinity of the known training amplitudes. But the memory doesn't depend on that aspect of the readout protocol—they could just as easily have scanned γ_o at a constant rate to detect an unknown γ_t.

Curiously, trained rafts behave like untrained rafts even for $\gamma_o < \gamma_t$ (or γ_{t1} for the two-memory raft). That means not only that training at γ_t has no effect on the raft response at $\gamma_o < \gamma_t$, but that shearing at $\gamma_o < \gamma_t$—which rearranges some of the bubbles—doesn't disrupt the memory of γ_t. Both of those features remain to be fully understood.

Cryptic memory

"We expected to see memory in this system," says Ganapathy. "But personally, I expected to see a clear memory signature only beyond the yield point, because that is where the system has been reconfigured enough to be subsequently read out." In fact, the memory works equally well for γ_t just above and just below γ_y: All three of the memory signatures shown in figure 2 are for strains less than γ_y. On the other hand, the memory works poorly for values far from γ_y in either direction.

That unexpected behavior offers a new path to exploring the nature of the yielding transition itself. Deforming a material at or above the yield strain doesn't make all of it yield uniformly; some parts flow freely while others remain rigid. Previous experiments from Ganapathy's group[5] showed that at γ_y, spatial correlations between the flowing and rigid regions are maximized, and the system's relaxation time diverges, just like at the critical point of a second-order phase transition. And recent simulations have shown that shearing a model glass at γ_y helps it find its way into an ultrastable, low-energy (but still disordered) configuration.[6]

There's something about γ_y, it seems, that efficiently rearranges particles and explores the space of possible configurations. What that has to do with memory depends on where and how the memory is stored in the system. If, for example, memory of each γ_t value is encoded at a particular length scale, that could help explain how the system can remember multiple γ_t values at the same time and why shearing at γ_y, which accesses all length scales, strengthens the memory signature.

But that's all speculation for now, because it's still not clear what makes a trained raft structurally different from an untrained one. So far, the only known way to tell them apart is by performing the readout protocol. Despite their best efforts, the researchers haven't found a way to tell the two apart based on the positions of the bubbles alone. An audience member at one of Ganapathy's talks once asked if the effect might somehow be exploited in cryptography. "I don't know the answer," he says, "but there might be advantages to this form of memory."

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A strain-based antenna paves the way for portable long-range transmitters

The piezoelectric device improves on the efficiency limits of small, conventional metal antennas without sacrificing bandwidth.

Very low-frequency (VLF) radio waves can carry signals through land and water with little attenuation. Unlike higher-frequency electromagnetic waves used for most communications, VLF waves are reflected by the ionosphere, and the space between it and Earth's surface acts as a waveguide through which the waves travel beyond the horizon. So, whereas higher-frequency waves travel in straight lines, VLF signals follow Earth's curvature and can transmit information to locations hundreds of kilometers away. The military uses VLF waves for navigation and communication with aircraft and submarines.

Although VLF signals are routinely generated, their use is limited by an antenna's size. To be reasonably efficient, an antenna's length should be at least a tenth of the signal's wavelength. For VLF waves, which are 3–30 kHz, the length would be more than a kilometer. Antennas whose length is much less than the signal's wavelength are considered "electrically small." They can still transmit VLF waves, but their nonradiative losses are large compared with the signals they transmit, so electrically small antennas are much less efficient than their larger counterparts. The VLF antennas used by the military are hundreds of meters tall, and even at that size they're electrically small. If they were portable, VLF antennas could be used by divers underwater, or by soldiers moving through underground mines or caves.

With their new piezoelectric antenna, Mark Kemp and coworkers at SLAC and their two industrial collaborators, SRI International and Gooch and Housego, are trying to get the best of both worlds.[1] Their prototype 9.6-cm-long lithium niobate transmitter, shown in figure 1, is much smaller than the approximately 10 km wavelength of the signal it generates, but it is more efficient than similarly small metal antennas. Although increased efficiency would normally be accompanied by a reduced bandwidth, modulating the antenna's resonant frequency allowed the researchers to maintain an effective bandwidth comparable to that of a small metal antenna.

Vibrating crystals

Piezoelectric crystals are often used as electronic oscillators because they vibrate with precise frequencies. Quartz crystals, for example, began being used about a century ago for timekeeping and as frequency references for radio sta-