From water's ephemeral dance, a new order emerges

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The freezing of a liquid into a crystalline solid is a ubiquitous and familiar phase transition that affects many aspects of our daily life. The crystallization of water, for example, has broad implications for our planet's climate and geography, and for diverse applications ranging from food and energy production to pharmaceutical formulation (1, 2). Nevertheless, numerous facets of crystallization remain incompletely understood because of the limited ability of experiments to resolve the molecular processes that initiate freezing in liquids. One particularly intriguing mystery is the possible connection between freezing and the dramatic changes observed in the dynamics of liquids cooled below their melting temperature T_m (3, 4). Writing in this issue of PNAS, Fitzner et al. (5) report results from computer simulations that offer a revealing glimpse into the microscopic connection between these phenomena in water.

The immutable Laws of Thermodynamics dictate that a liquid will freeze when cooled below T_m, but they do not specify how, or on what time scale, this process will occur (1). Our experiences with liquid water, which readily freezes in the environment when cooled below its melting point $T_\mathrm{m} = 0\,^\circ\mathrm{C}$ at ambient pressure, may suggest that crystallization is relatively swift. Yet, it is often delayed, or arrested indefinitely, in other scenarios. Without impurities or surfaces to promote crystallization, gentle cooling below T_m produces a supercooled liquid phase that can survive in a state of precarious metastable equilibrium (1, 6). Rapid cooling below the glass transition temperature $T_\mathrm{g} \ll T_\mathrm{m}$, by contrast, produces an amorphous solid known as a glass that will not crystallize on experimentally observable time scales (6, 7). For water, the supercooled liquid has been studied down to $-46\,^\circ\mathrm{C}$ (8); at atmospheric pressure, it can exist as a glass below $T_\mathrm{g} \approx -137\,^\circ\mathrm{C}$ (7).

Although the molecular processes that lead to crystallization are kinetically arrested in glasses, this is not the case in supercooled liquids. Thermal fluctuations in supercooled liquids drive molecular motions (translations and reorientations) that enable their structure to relax on finite time scales (3). The characteristic time for structural relaxation, however, increases rapidly as T is decreased, foreshadowing the impending arrest of these processes at T_g. This dramatic slowing manifests as an increase in the liquid's shear viscosity. It also coincides with the onset of non-exponential behavior in the relaxation spectra measured by dielectric and NMR spectroscopy (3). One explanation suggests that this non-exponential behavior arises from molecules in distinct spatial regions of the supercooled liquid relaxing at different rates (3, 4). This interpretation is supported by direct observation of dynamical heterogeneity (DH) in computer simulations of supercooled liquids (4) and in microscopy experiments on dense particulate suspensions near the colloidal glass transition (9). A vivid picture of DH emerges from these studies: at a given instant in time, supercooled liquids resemble disordered mosaics of active and dormant regions where molecules are more and less mobile, respectively. The mosaic is fluid due to the ephemeral nature of these domains, which continuously grow, shrink, disappear, and reappear over time as the supercooled liquid relaxes.

Within this dynamically heterogeneous mosaic, collective molecular rearrangements lead to the spontaneous formation of small nuclei with crystal-like order (1, 10). Although freezing of the supercooled liquid is thermodynamically favorable, small nuclei are unstable due to the free energy penalty associated with forming a crystal-liquid interface at their surfaces. As a result, they are short-lived and melt back into the liquid. Rare fluctuations in the supercooled liquid, however, eventually lead to the formation of a stable nucleus large enough to overcome this penalty and seed growth of the crystal phase. This event signals the imminent demise of the supercooled liquid and the beginning of its transformation into a crystalline solid.

While these physical pictures of DH and crystal nucleation qualitatively capture the behavior of many supercooled liquids, the microscopic connection between these phenomena remains murky. It is not clear if crystal nuclei preferentially develop in the active or dormant regions in supercooled liquids. Similarly, it is not known if specific structural motifs in these domains promote crystallization. Computer simulations suggest that mobile and immobile domains in supercooled water, for example, are associated with different locally favored structural motifs in the liquid (11) (Fig. 1A–D). Low-mobility regions tend to be populated with molecules that have an open tetrahedral coordination structure resulting from their hydrogen bonds with four nearby neighbors (Fig. 1A). These motifs resemble the ideal tetrahedral molecular configurations found in normal hexagonal ice (ice Ih), but are distorted and not organized in periodic arrangements. In high-mobility regions, this local tetrahedral order is partially disrupted by intru-

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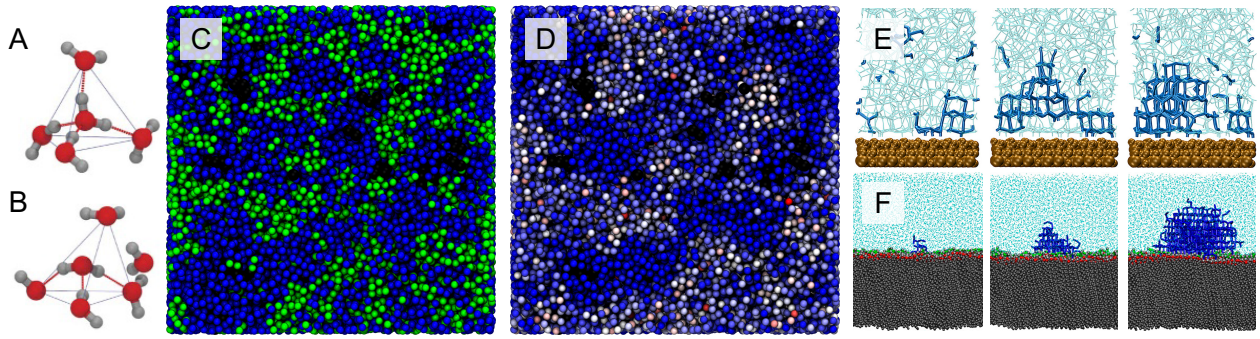

Fig. 1. (A,B) Liquid water's two locally favored structural motifs. Adapted from ref. 11. (C) Correlation between local structure and DH in a 32,000 molecule MD simulation of the TIP5P water model at $-33\,^{\circ}\mathrm{C}$ and 1 bar. Molecules with coordination structures similar to (A) and (B) are colored blue and green, respectively. (D) Same as (C) but with molecules colored using a blue-white-red scale to indicate low-to-high mobility. Ice-like molecules in (C) and (D) are colored black. Only water's oxygen atoms are shown for clarity. Structure and mobility were characterized using the ζ^{CG} and $\Delta r_{\max}(\tau_4)$ metrics defined in ref. 11. Heterogeneous ice nucleation on a kaolinite surface (E) and on a soft self-assembled monolayer (F). Left to right arrangement indicates progression of time. Panels (E) and (F) were adapted with permission from refs. 17 and 18, respectively. Copyright 2017 and 2018 American Chemical Society.

sion of an additional molecule into water's coordination shell (Fig. 1B). Like the active and dormant regions, these two local motifs are transient and rapidly interconvert during the liquid's relaxation process.

The existence of two locally favored molecular motifs in water has been invoked to explain many of its unusual thermophysical behaviors, including its density maximum at $4\,^{\circ}\mathrm{C}$ and ambient pressure, its anomalous increase in compressibility upon cooling at low temperatures, and its ability to form at least two glass phases (6, 7, 12). It has also been controversially hypothesized that these motifs may give rise to a phase transition between two distinct liquid forms of supercooled water under very cold conditions, where measurements of liquid properties are frustrated by the rapid nucleation of ice (13–15). For freezing, the strongly tetrahedral motifs have been implicated in the formation of ice-like nuclei (16), hinting that crystallization in supercooled water may preferentially begin in its dormant regions. Alternatively, the development of crystalline order may be kinetically hindered in domains with low molecular mobility. Direct evidence in support of either of these hypotheses, however, has thus far been elusive.

The computer simulations of supercooled water by Fitzner et al. (5) address this knowledge gap. Their molecular dynamics (MD) simulations of the TIP4P/ice model of water – the current gold standard for describing freezing behavior – elucidate where ice nucleation begins. They find that a disproportionate number of molecules in the largest ice-like clusters observed in their simulations reside in low-mobility regions, much more than would be expected in the absence of any correlation. Similarly, far fewer than expected molecules in the largest crystalline clusters are found in high mobility regions. This key result indicates that there is strong spatial overlap between dormant and crystal-forming regions, pointing to the low-mobility domains as favorable locations for ice to form. Even more intriguing, however, is the temporal correlation revealed by their study. They observed that the development of ice-like local order in the molecules composing the largest cluster is preceded by a drop in their mobility. These processes are well-separated in time, suggesting that they may be viewed as distinct steps in nucleation.

Fitzner et al. examined the formation of small, unstable nuclei in their study of TIP4P/ice, but did not observe crystallization because it occurs on time scales that are beyond those readily accessible in MD simulations of this model. Freezing of TIP4P/ice has been previously studied using advanced simulation algorithms, but those calculations were remarkably demanding (2). To determine if successful crystallization events also begin in dormant regions of the liquid, Fitzner et al. (5) performed a second set of simulations using the coarse-grained mW model of water. The mW model accurately predicts many properties, but it is about two orders of magnitude faster to simulate due to its simplified representation of water molecules (16). Analysis of the mW crystallization trajectories demonstrates that successful ice nucleation events almost always begin in regions of low molecular mobility, confirming the intriguing picture suggested by the simulations of TIP4P/ice. It also shows that the dormant regions grow along with the ice nuclei, indicating that large ice-like clusters profoundly alter the dynamics of the surrounding liquid.

This study sheds new light on the role of molecular mobility in ice nucleation, intimating a deep connection between DH, crystallization, and local structural motifs in supercooled water. It remains to be seen, however, if these findings can be generalized to other liquids. Technologically important substances such as silica, silicon, carbon, and germanium also form tetrahedral liquids that behave similarly to water in many regards (15). It is therefore tempting to speculate that tetrahedral motifs and local mobility may play a similar role in crystal nucleation in these substances, but that has yet to be confirmed. Likewise, DH is observed in supercooled liquids very unlike water (3, 4). In some, DH is connected with locally favored motifs in the liquid that have been implicated in crystallization. In others, this connection is not so clear (19). The computational approaches employed in ref. 5 may help address these open questions.

Despite advances in unraveling the crystallization mechanism of bulk water (2, 5, 16, 20), ice formation in almost all practical settings is either promoted or hindered by the presence of solutes or surfaces that affect local molecular mobility and ordering in the liquid. Recent studies have provided new insight into the mechanisms by which ice may nucleate on mineral dust in the atmosphere (17) and on the soft surfaces of self-assembled monolayers (18) (Fig. 1E,F), but fundamental understanding of crystallization in heterogeneous environments is still lacking. Future progress in this area will advance myriad applications ranging from the cryopreservation of tissues and organs to the design of icephobic surfaces for aircraft. While much new knowledge will come from cleverly designed experiments, computer simulations will undoubtedly play

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an important role. As the recent investigations by Fitzner et al. (5) and others (2, 16–18, 20) demonstrate, these methods can resolve with striking clarity the rare, collective rearrangements in supercooled water from which ice is born.

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References.

1 Debenedetti PG (1996) *Metastable liquids: Concepts and principles*. (Princeton University Press).
2 Haji-Akbari A, Debenedetti PG (2015) Direct calculation of ice homogeneous nucleation rate for a molecular model of water. *Proc Natl Acad Sci USA* 112(34):10582–10588.
3 Ediger MD (2000) Spatially heterogeneous dynamics in supercooled liquids. *Annu Rev Phys Chem* 51(1):99–128.
4 Berthier L (2011) Dynamic heterogeneity in amorphous materials. *Physics* 4:42.
5 Fitzner M, et al. (2019) Ice is born in the low-mobility regions of supercooled liquid water. *Proc Natl Acad Sci USA*.
6 Debenedetti PG (2003) Supercooled and glassy water. *J Phys: Condens Matter* 15(45):R1669.
7 Handle PH, Loerting T, Sciortino F (2017) Supercooled and glassy water: Metastable liquid(s), amorphous solid(s), and a no-man's land. *Proc Natl Acad Sci USA* 114(51):13336–13344.
8 Kim KH, et al. (2017) Maxima in the thermodynamic response and correlation functions of deeply supercooled water. *Science* 358(6370):1589–1593.
9 Hunter GL, Weeks ER (2012) The physics of the colloidal glass transition. *Rep Prog Phys* 75(6):066501.
10 Jungblut S, Dellago C (2016) Pathways to self-organization: Crystallization via nucleation and growth. *Euro Phys J E* 39(8):77.
11 Shi R, Russo J, Tanaka H (2018) Origin of the emergent fragile-to-strong transition in supercooled water. *Proc Natl Acad Sci USA* 115(38):9444–9449.
12 Anisimov MA, et al. (2018) Thermodynamics of fluid polyamorphism. *Phys Rev X* 8(1):011004.
13 Poole PH, Sciortino F, Essmann U, Stanley HE (1992) Phase behaviour of metastable water. *Nature* 360:324–328.
14 Hestand NJ, Skinner J (2018) Perspective: Crossing the widom line in no man's land: Experiments, simulations, and the location of the liquid-liquid critical point in supercooled water. *J Chem Phys* 149(14):140901.
15 Palmer J, Poole P, Sciortino F, Debenedetti PG (2018) Advances in computational studies of the liquid-liquid transition in water and water-like models. *Chem Rev* 118(18):9129–9151.
16 Moore EB, Molinero V (2011) Structural transformation in supercooled water controls the crystallization rate of ice. *Nature* 479:506–508.
17 Glatz B, Sarupria S (2018) Heterogeneous ice nucleation: Interplay of surface properties and their impact on water orientations. *Langmuir* 34(3):1190–1198.
18 Lupi L, Hanscam R, Qiu Y, Molinero V (2017) Reaction coordinate for ice crystallization on a soft surface. *J Phys Chem Lett* 8(17):4201–4205.
19 Malins A, Eggers J, Tanaka H, Royall CP (2013) Lifetimes and lengthscales of structural motifs in a model glassformer. *Faraday Discuss* 167(0):405–423.
20 Lupi L, et al. (2017) Role of stacking disorder in ice nucleation. *Nature* 551:218–222.

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