

## Physical chemistry

## Sculpting ice out of water

Srikanth Sastry

Computer simulations are illuminating the molecular processes through which water is transformed into ice — and offering insight into crystallization more generally.

When water becomes cold enough, it freezes into ice. Capturing this everyday process on a computer, however, is far from routine. Although there have been simulations of water crystallization, researchers have usually managed this only by creating artificial conditions — for example, by confining the water in a restricted space<sup>1</sup>. In such studies, including a recent one in which there was spontaneous crystallization<sup>2</sup>, the resulting crystallized state was not the usual hexagonal ice that forms at atmospheric pressure.

On page 409 of this issue, Matsumoto, Saito and Ohmine<sup>3</sup> report the first successful simulation of the formation of hexagonal ice. Their results open the way to understanding the complex kinetics of how water freezes, at the microscopic level. Understanding the kinetics of such phase transformations is important in many areas, from designing new materials<sup>4</sup> to determining protein structure by crystallography<sup>5</sup>.

The freezing of water into ice is the most familiar example of a first-order phase tran-

sition — the transformation of matter from one state to another that brings about a marked change in properties. When water is cooled below the freezing point, 0 °C at ambient pressure, the regular structure of ice, with strong attractive interactions between molecules, becomes the thermodynamically preferred state. Nevertheless, it is relatively easy to cool water below 0 °C without the liquid crystallizing. Despite the fact that, in this supercooled state, liquid water is thermodynamically less stable than ice, it remains stable as long as there are no large changes or fluctuations in the system: if a perturbation exceeds a certain threshold, the liquid will transform into ice.

The threshold to crystallization is defined by the formation of a 'critical nucleus', which is expected to be a crystallite of ice that is large enough not to dissolve back into the liquid, and which will grow until the entire sample is transformed into ice. Agents that can cause nucleation include dirt particles, around which a nucleus forms (this is how artificial rain is seeded), or mechanical

agitation (shaking the container). Barring such external help, nucleation must occur spontaneously: ever-present thermal fluctuations can occasionally transform local regions of the liquid from liquid-like structure to a more crystal-like configuration. When such fluctuations cross the critical threshold, nucleation and growth of ice ensue.

Matsumoto *et al.*<sup>3</sup> have tried to work out the details, at the molecular level, of how the critical nucleus forms and grows in water. They simulated the dynamics of water molecules, using knowledge of the forces between the molecules, to trace the evolution of molecular arrangements over microsecond timescales, which are long by present-day standards of computer simulation. And this is where the difficulty arises. Matsumoto *et al.* needed to generate many microsecond-long time histories (or trajectories) in order to find even one trajectory that led to crystallization. The reason for the difficulty in finding the crystal state, they say, is the complexity of water's potential-energy surface — this is the landscape-like map that describes how the total energy of the collection of water molecules varies as the individual molecules move.

Each configuration of molecules corresponds to a specific value of potential energy for the system. Configurations can be grouped together such that the potential energy varies smoothly between them, and a path connecting them exists along which there will be no potential-energy barrier.

## Materials science

## Repellent behaviour

Rain and condensation can make it difficult to see through spectacles or vehicle windscreens. One solution to this everyday problem lies in coating the optical surface with an ultra-water-repellent, transparent film. But for manufacturing purposes, the coatings on plastic surfaces (for example, lightweight spectacle lenses) need to be produced at temperatures below 100 °C to avoid damaging the surface.

Writing in *Chemical Vapor Deposition* (8, 47–50; 2002), Yuning Wu *et al.* report a strategy for producing ultra-water-repellent coatings that can be carried out at room temperature. They used a technique called microwave plasma-enhanced chemical-vapour deposition to deposit films of an organic monomer, trimethylmethoxysilane (TMMOS), at a partial pressure of 50 Pa, on a glass or plastic surface. The resulting

coatings are highly transparent and give the required high contact angle (above 150°) between the water and the coating (upper figure), and so a less wettable surface.

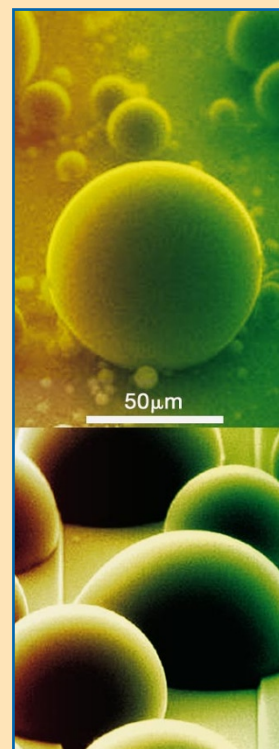
What is the cause of this ultra-water-repellence? The wettability of surfaces is governed by surface energy, chemistry and texture. The surface of the TMMOS film is believed to be terminated with methyl groups. So Wu *et al.* compared their coating with a chemically similar film, methyl-terminated self-assembled monolayers. These turned out to be much more wettable, with a water contact angle of about 100° (lower figure). A film of TMMOS prepared at a lower partial pressure (18 Pa) also resulted in a lower water contact angle (110°).

The answer to the ultra-water-repellent behaviour of TMMOS therefore appears to lie instead in its surface texture. Micrographs of the

coatings deposited at 50 Pa revealed non-wettable columns of the deposited film a few hundred nanometres in diameter, with pores in between. The authors suggest that the film created at 18 Pa was less water-repellent because its molecules are more densely packed and there are no pores. The methyl-terminated self-assembled monolayer appeared to be perfectly smooth.

The porous nature of the films deposited at 50 Pa means that the surface consists of both air and TMMOS. Wu *et al.* propose that the apparent surface energy of the film is therefore reduced, increasing its non-wettable properties. The authors don't expand on their theory to consider the events at the molecular scale. But the performance of the coatings shows that they could be of real use to spectacle-wearers out in the rain, or coming in from the cold.

Rosamund Daw



(An example would be a pair of configurations that differ only by a small twisting of one molecule with respect to its neighbours.) To simplify things further, each group of configurations can be represented by the configuration possessing the lowest energy in the group (that is, the local energy minimum). The dynamics can then be viewed as the system hopping from one minimum to another, requiring an intermediate increase in energy to cross each potential-energy barrier. These barriers, and the complexity of the pathway to crystalline structure, which defines the minimum with the lowest energy, determine the rate of crystallization.

Matsumoto *et al.*<sup>3</sup> contend that, in contrast to simple atomic liquids such as argon, the pathway leading from the liquid to the lowest energy — crystalline — state is not smooth in the case of water. This idea is supported by an analysis of small clusters of water molecules by Wales *et al.*<sup>6</sup>. The explanation may lie in the fact that an open tetrahedral structure for the water molecules is energetically preferred, and that the hydrogen bonds between oxygen atoms sharing a common hydrogen atom are relatively flexible. So water can take on a globally disordered structure, but still retain the benefits of energetically favourable local arrangements.

A remarkable observation by Matsumoto *et al.* is that the critical nucleus that causes crystallization is itself not crystalline. In fact, there are other instances where the critical nucleus does not have the same structure as the equilibrium phase it nucleates (for example, the critical nucleus for a model liquid that will form a stable face-centred cubic crystal is a body-centred cubic crystallite<sup>7</sup>). And in modelling protein crystallization, ten Wolde and Frenkel<sup>5</sup> showed that the initial nucleus is liquid-like when crystal nucleation takes place near a metastable critical point — in the phase diagram of the system they study, the liquid–gas critical point is pushed below the line at which the fluid is transformed to the solid, and therefore occurs in metastable conditions. Indeed, a metastable liquid–liquid critical point has been proposed for water<sup>8</sup>, so this idea has some appeal.

But there are potentially significant differences between the cases for water and proteins: the difference in density between the parent phase and the crystal that is nucleated is smaller in water; and the metastable critical point in water, if present, must be at much lower temperatures and higher pressures<sup>9</sup>. A more useful comparison in this context may be with liquid silicon<sup>10</sup>, for which rapid crystal nucleation occurs in conditions in the vicinity of a weak, first-order transition. Although it shares the loose-packed tetrahedral structure of water, silicon's bonding network is much less flexible. Sorting out the interplay of various factors in these systems would be a productive exercise.

To progress beyond the results of Matsumoto *et al.*, we need to study crystallization over a wider range of temperatures, and also to exploit methods<sup>7</sup> for directly evaluating the free-energy barrier to nucleation. The computational effort required for the first task is formidable, while the second approach requires the identification of a small number of variables, or order parameters, for describing the progress of ice nucleation reliably. Matsumoto and colleagues' report on this point is discouraging — their attempts to identify useful order parameters for water have so far been unsuccessful.

The example of protein crystallization<sup>5</sup> shows that a systematic approach to a complex question — the possibility of, and optimal strategy for, crystallizing proteins — is closely related to the seemingly much simpler question of how water freezes. Understanding the behaviour of water could help us to tackle other questions, such as when a liquid readily forms a disordered glass state<sup>11</sup> — an important issue in designing non-crystalline materials. Water may be a better starting point for addressing this

question than are atomic liquids. Given the significance of the general problem of crystal nucleation and growth, and the richness that the example of water brings to the question, work that builds on the results of Matsumoto *et al.*<sup>3</sup> is bound to be rewarding. ■

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## Neurobiology

# Serotonin sustains serenity

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An elegant variation on conventional gene-knockout techniques can delete a gene at specific times and locations in mice. The approach shows when and where a serotonin receptor protein is needed during development.

On page 396 of this issue, Gross and colleagues<sup>1</sup> look in depth at how serotonin, one of the chemical messengers that nerve cells use to communicate, is involved in anxiety. Perhaps one of the best known of these messengers, or neurotransmitters, serotonin has a role in many different neurobiological processes. For example, it helps to regulate our moods — a fact that has been well established since the 1950s, with the discovery that drugs that deplete serotonin precipitate depression whereas increasing serotonin levels has antidepressant effects. The idea that serotonin might also affect anxiety was first suspected in the 1980s following the serendipitous finding that buspirone, a drug developed to treat psychotic patients, is also useful for treating anxiety disorders, and stimulates a type of serotonin-detecting molecule in the body, the serotonin<sub>1A</sub> receptor. Later came the discovery that mice that have been genetically engineered to lack this receptor, and so cannot respond normally to serotonin, show increased 'anxiety-like' behaviour<sup>2–4</sup>.

But the underlying mechanisms have been elusive. For instance, the relevant brain regions have not been delineated. Moreover, the findings in receptor-deficient mice

appear to contradict observations that compounds that block serotonin<sub>1A</sub> receptors do not cause anxiety in adult mice. Gross *et al.*<sup>1</sup> substantially clarify these issues. By using mice in which the serotonin<sub>1A</sub> receptor can be knocked out at will, the authors show that the absence of the receptor in newborns does indeed lead to anxiety-like behaviour, whereas its knockout during adult life has no effect. Gross *et al.* also discriminate between the role of the receptors in the hindbrain and in forebrain structures such as the hippocampus and cerebral cortex.

Conventional gene-knockout techniques are powerful tools for working out what a protein does. But they have major limitations compared with using drugs (which might, for example, activate or inhibit the protein of interest). Genes tend to be knocked out during embryonic life, generally affecting the whole organism throughout its lifetime. By contrast, a drug can be administered at any time and, in the brain, can be injected into specific areas.

The approach adopted by Gross *et al.*<sup>1</sup> is an ingenious way of addressing the shortcomings of gene knockouts, providing time- and tissue-specific deletion and restoration of serotonin<sub>1A</sub> receptors. To achieve time-