# CELL PHYSICS

Do living cells exploit statistical physics? It's strange that the question need be asked, as phase transitions and critical phenomena are universal features of condensed matter, and of many-particle systems more broadly. There is no obvious reason why the mere fact of being alive should confer exemption, and indeed phase transitions are seen in biology at the macroscale of communities of organisms, including humans — in flocking behaviour, say, and crowd movements. Yet they have, until recently, been afforded little attention in cell biology, where the dominant paradigm of genetic control has been tacitly supposed to supersede the influence of such generic, physical influences.

That's now changing. There is a growing body of evidence suggesting that cells are constructed to actively manipulate and exploit phase changes. It has long been recognized that the clustering ('rafting') of different lipids in the two-dimensional fluids of cell membranes is an example of liquid–liquid phase separation that permits the sequestering of membrane proteins, with consequences for exo- and endocytosis and cell signalling[1]. Phase separation within the cytoplasm creates structures such as the protein–RNA complexes called P granules involved in germline formation, and the liquid-like nucleoli within which ribosomes are formed[2]. A phase transition analogous to capillary drying (abrupt expulsion of water) may drive the hydrophobic collapse of proteins and formation of some multi-subunit protein arrays[3,4]. Phase transitions create a large response to small changes in environmental conditions: a widely useful phenomenon that might result in many biological systems, such as neuronal networks and protein conformations, being tuned to sit close to a phase boundary[5].

That possibility is further supported by a proposal that the two-dimensional liquids of biological membranes might operate close to the miscibility critical point of its components[6]. In this situation they would experience large fluctuations that can give rise to a relatively long-ranged Casimir force, an attractive interaction that could be exploited in the rearrangements that accompany cell signalling.

The most familiar manifestation of the Casimir force results from the restriction in wavelength of vacuum fluctuations in a confined space, creating an effective pressure that draws the confining surfaces together. Fisher and de Gennes showed that an analogous effect — a 'critical Casimir force' — operates at the critical point of miscible fluid phases, where again an interaction is caused by the constraints on fluctuations in fluid composition that can become very long-ranged close to criticality[7]. It's a real effect, as recent experiments demonstrated[8].

Some biological membranes contain surprisingly large (around 100 nm) rafts of segregated lipids that seem to arise from proximity to a

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two-dimensional critical point. Using a lattice model of these structures, Machta *et al.* calculate that the resulting critical Casimir force experienced by membrane-bound proteins, although rather weak, has a longer range (of the order of tens of nanometres) than the screened electrostatic potentials that may dominate at shorter distances[6]. Cell signalling following the binding of a substrate to a protein is commonly accompanied by a reorganization of the proteins in the membrane, which Machta *et al.* suggest is mediated by these critical Casimir forces. If so, it suggests that cell membranes embody an implicit understanding of their ineluctable statistical physics.  ❏

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SUPERHYDROPHOBIC SURFACES

# Leidenfrost becomes a fakir

When cooled in water from high temperature, superhydrophobic surfaces stabilize the vapour layer on them, thus avoiding the typical vapour explosions associated with the nucleation of bubbles.

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There are two classical ways to make a solid water-repellent. It can either be heated to at least 200 °C to make water levitate on a cushion of its own vapour (for example, as occurs on any sufficiently hot frying pan) or the solid can be coated with a textured hydrophobic material at room temperature. The former was first described in 1756 by the German physician Leidenfrost[1]. The latter is known as the fakir state[2], in which the water sits on top of the micronails of the texture and is suspended above the air entrapped between them.

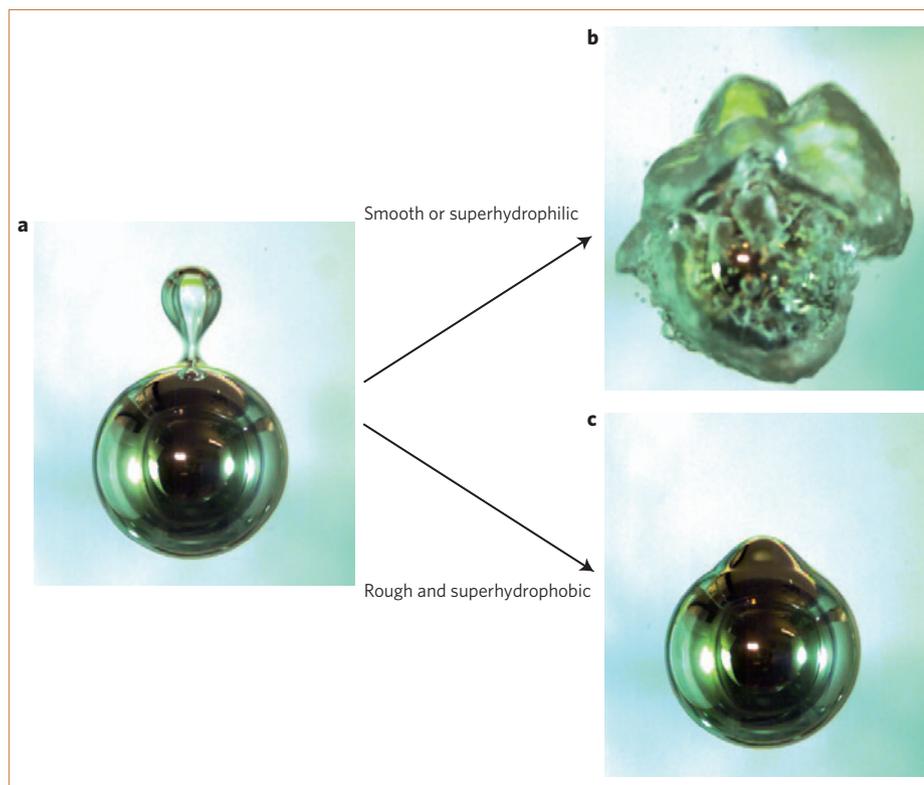Writing in *Nature*, Sigurdur Thoroddsen and colleagues show that the Leidenfrost

**Figure 1 |** Hot steel balls (2 cm in diameter) cooling in liquid water[3]. **a**, A sufficiently hot ball is covered by a thick film of vapour (this is the Leidenfrost state), as can be seen from the shiny water/vapour interface. Big bubbles resulting from buoyancy are periodically released at the top of the ball. **b**, If the ball is smooth (hydrophilic or hydrophobic) or superhydrophilic, at some point during cooling the Leidenfrost state is lost in an explosive transition corresponding to the nucleation of many disconnected bubbles at the ball's surface. **c**, If the ball is superhydrophobic (therefore, rough), the Leidenfrost state is stabilized down to 100 °C. The bump at the top of the ball indicates that vapour is still produced.

and fakir states can be combined on appropriately textured superhydrophobic surfaces to considerably extend the temperature regime where liquids on hot surfaces can be sustained by vapour films[3]. To show this, the researchers used 2-cm-diameter steel balls of various wetting properties — superhydrophilic, hydrophilic, hydrophobic and superhydrophobic. Each ball was heated to at least 400 °C, immersed in a large bath of water and its position fixed magnetically. In this inverse Leidenfrost situation, first reported by Faraday[4], the ball is also covered by a thick (0.1 mm) continuous layer of vapour (Fig. 1a). At the initial high temperatures, buoyancy makes the vapour flow upwards along the surface of the ball, leading to the regular emission of bubbles at the top. However, after about 20 s, for balls with smooth hydrophilic or hydrophobic surfaces the temperature at the ball's surface reaches the so-called Leidenfrost point, where an explosive transition to classical boiling characterized by a massive production of disconnected bubbles takes place (Fig. 1b). Boiling makes

the transfer of heat much more efficient, but an explosive production of vapour can be detrimental, for example, in cooling devices such as those used in nuclear plants.

Hence, when hydrophilic textures are added to the surface, boiling is promoted[5,6], and the Leidenfrost point gets shifted to higher temperatures. However, Thoroddsen and co-workers show that the situation is entirely different when the ball's surface is rough and superhydrophobic: the vapour film is stabilized by the presence of the textures, so that the system keeps its insulating properties while it is cooling and it does not suffer a transition towards explosive boiling (Fig. 1c). Indeed, superhydrophobic textures preserve the continuous vapour film down to the boiling point. Similarly, heating a water drop on a superhydrophobic spoon from room temperature up to a few hundred degrees would not produce any discontinuous transition to the Leidenfrost state; instead, it would just thicken the vapour film below the liquid.

It is ingenious to exploit the presence of a continuous plastron of air to stabilize

the Leidenfrost film on superhydrophobic surfaces that are immersed in water. As the surface temperature decreases, solid–liquid contact can establish at the top of the textures without producing a vapour explosion, as the vapour nucleating at these contacts is incorporated into the plastron. Hence, it becomes possible to bring about the Leidenfrost state at temperatures just above the boiling point[3,7], where it was considered not to happen. It will be interesting to study the vapour film at these lower temperatures in detail, in particular, the way its thickness gradually increases from the size of the texture features (~1 μm) to the typical thickness (100 μm) at the temperature where the Leidenfrost phenomenon is generally observed (> 200 °C for water). Moreover, thin Leidenfrost films should have novel friction and thermal properties, and their thinness might also modify the stability of Leidenfrost puddles above them. Clearly, this 'cold Leidenfrost' regime remains to be described.

Furthermore, the work by Thoroddsen and colleagues suggests that the failure of water to levitate between 100 °C and the Leidenfrost point on non-superhydrophobic materials should be reconsidered from a different perspective. The liquid/vapour interface below a levitating drop can be wavy[8] owing to the motions observed in both the vapour (squeezed by the liquid above) and the liquid (where temperature differences can produce flows). A thick vapour film can resist these fluctuations, but on cooler surfaces the film becomes thinner and the fluctuations of the interface may locally induce solid–liquid contacts. These contacts will propagate if the surface is hydrophilic or even slightly hydrophobic, and cause the suppression of levitation and the generation of vapour explosions; on the contrary, because a superhydrophobic surface is preferably coated by air (or vapour) rather than by water, the contacts might retract and heal, preserving the levitation of the liquid down to the boiling point. ❐

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