polarization would ever be measured in the right arm. On the contrary, the authors show that polarization can still be found in the right arm. The polarization has then been effectively 'disembodied' from the photon travelling in one arm of the interferometer, a bit like the grin of the Cheshire cat in Alice in Wonderland.

Despite having a very different aim than game testing, this scheme shares a common feature with the approach used by the inventor. It relies both on a specific preparation of the quantum system and on a clever post-selection — the interaction with the set-up taking place between these two steps. Consequently, just like in the story, several events must first be rejected from the experimental data set before reaching the conclusion. This time, however, the post-selection of runs is not decided based on notes written in a log-book, but rather on the outcome of a quantum measurement applied to the photon exiting the interferometer.

Specific pre- and post-selections alone don’t yet allow the authors to achieve the desired result in the quantum case. One more constraint is needed — the interaction with the photon in either arm of the interferometer must be weak, in the sense of not having a significant impact on it. This excludes direct quantum measurements to be performed there, for instance, as they would produce too large a disturbance on the state.

Weak measurements are examples of weak interactions in which the position of a pointer (the needle of the measurement apparatus) is only slightly coupled with the degree of freedom to be measured. When the effect of this coupling is smaller than the intrinsic uncertainty of the pointer’s position, an individual reading of this position yields a random outcome, but its average over many runs indicates the value of the quantity of interest and thus provides information about the measured system. Owing to their negligible disturbance, weak measurements have been used to estimate several quantities simultaneously, including incompatible ones, as demonstrated in the direct measurement of a wavefunction. Aharonov et al. use this feature to show that weak measurements in the right arm could simultaneously detect the polarization of the photon and not see the photon itself directly.

The initial proposal by Aharonov and colleagues has sparked interest in the form of extensions and further discussions. Ibnouhsein and Grinbaum, for instance, consider the possibility of isolating properties of several quantum systems simultaneously, whereas Guryanova et al. asks whether the polarization of the photon could be disembodied along more than one direction. DiLorenzo proposes a different definition for these ‘quantum Cheshire cats’ by considering correlations in the pointer position of two weak measurements. Finally, Matzkin and Pan consider photons traveling in an interferometer with three arms, making a link to the three-boxes paradox. Although limited to weak interactions and requiring a successful post-selection, the Cheshire cat scheme opens the striking possibility of talking about a property without its physical support. The best way to achieve this in experiment and the possible implications are however still subject of discussion and a more precise understanding of these aspects would be most welcome.

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CRystallization

Colloidal suspension

According to classical nucleation theory, a crystal grows from a small nucleus that already bears the symmetry of its end phase — but experiments with colloids now reveal that, from an amorphous precursor, crystallites with different structures can develop.

László Gránásy & Gyula I. Tóth

Colloidal suspensions consist of small, typically micrometre-sized, particles floating in a carrier fluid: their ability to crystallize is a feature often used to explore the process of nucleation, during which tiny crystallites form through thermal fluctuations of the non-equilibrium (undercooled or supersaturated) fluid. In a study published in Nature Physics, Peng Tan and colleagues uncover the possible pathways through which a colloidal suspension can evolve from the liquid to the solid state. Although mounting evidence in recent years has supported a process of two-stage nucleation in simple liquids, the new work provides long-awaited details on its structural aspects.
In the colloidal crystallization experiments performed by Tan and colleagues, the solvent is a mixture of non-polar and weakly polar solvents. By changing the polar/non-polar ratio of the solvent's components, the (soft-repulsive) interaction between the colloidal particles can be tuned. Essentially, this means that the crystal structure of the nucleating state can be regulated: body-centred cubic (bcc) or face-centred cubic (fcc). The authors have also investigated crystallization in a hard-repulsive system, where the end-state is a random mixture of fcc and hexagonal close-packed (hcp) symmetries — known as random hcp. Using three-dimensional confocal microscopy, they analysed the evolving configurations in terms of so-called bond-order parameters — rotationally invariant measures for the structure of the first- and second-neighbour shells around any given particle. From an examination of bond-order parameters and solid-bond numbers (for a given particle, the solid-bond number is the number of neighbours lying within the crystalline phase), Tan et al. distinguished three different states of crystallizing matter: liquid, precursor and nucleus. To compute the bond-order parameters, they introduced a method that corrects for the randomizing effect of thermal fluctuations, yielding particles with temporary, non-crystalline coordination even in crystalline or crystal-like regions — an approach that helps to identify the local structure.

From these experiments, it is clear that in all these colloidal systems the observed crystalline phases nucleate through an intermediate step. First, an amorphous precursor forms with mainly hcp-like short-range order, but also with some minor bcc- and fcc-like content (Fig. 1). Then, during the actual crystallization process, the precursor develops into a crystalline phase that is determined by the nature of the interparticle interaction (soft- or hard-repulsive). Fcc-, bcc- or hcp-like precursors can evolve into crystalline nuclei of any of these symmetry types. The densities of the precursors lie between those of the bulk crystalline and the liquid phases. However, the spatial distributions of density and structure in the crystallizing liquid do not seem to correlate — a finding that deserves further investigation. And although these results extend our knowledge of crystal nucleation substantially, they also raise intriguing questions: why does one have non-crystalline precursors in the first place, and how general is the presence of amorphous precursors in crystal nucleation?

Let us address the second question first. There are several cases in which a structurally disordered precursor has been seen to assist the formation of a crystalline phase: optical studies on colloids, which show that crystal nucleation happens inside dense, low-symmetry amorphous precursors; Monte Carlo simulations of the hard-sphere system, in which dense, amorphous clusters form first, assisting the nucleation of crystallites; theoretical studies that predict a dense fluid precursor for globular proteins and the Lennard–Jones system; and dynamical density functional studies based on the so-called phase-field crystal (PFC) technique (a molecular theory of crystalline freezing with an effective potential approximating the interactions between the weakly charged colloids), which demonstrate that crystallization starts with the nucleation of amorphous droplets of density between that of the bulk crystalline and liquid phases.

Bond-order analysis of PFC results reveals hcp-like short-range ordering for the precursor; the corresponding order-parameter map is less structured than for colloid experiments, however. In addition, in the PFC simulations a substantial amount of another type of precursor forms, having ‘liquid-like’ short-range order: its bond-order distributions coincide with those of the bulk liquid. Accordingly, this second type of amorphous precursor cannot be distinguished from the liquid by bond-order analysis. So, what Tan et al. identified as liquid could in part consist of solid precursors of liquid-like short-range order, and, in the present state of affairs, the amorphous precursors initiating crystallization could still be mixtures of domains of liquid- and crystal-like neighbourhoods.

But why should such amorphous precursors form anyway? A general argument has been given by Lutsko and Nicolis, suggesting that it is easier, from a free-energy-minimization point of view, to crystallize by passing through a metastable dense fluid state rather than ordering and densifying simultaneously as assumed in the classical picture of crystallization. A recent theoretical tour de force using the density-functional approach (the only practicable molecular theory of crystalline
freezing) offers another clue\(^\text{16}\) in highly non-equilibrium liquids, solidification starts with spherical density waves — resulting in a kind of ‘onion structure’ — as they are energetically favourable to small crystalline clusters. This finding may offer a natural explanation of the amorphous precursor: except for the first-neighbour clusters, these concentric density waves are incompatible with a long-range crystalline structure. The interference of the onion structure with thermal density fluctuations may account for the observed preference for early-stage amorphous solidification.

Putting everything together, one has the following scenario in the language of continuum theory (in terms of time-averaged particle density). First, the highly symmetric homogeneous liquid state (characterized by a uniform particle density) loses its translational symmetry when the onion structures form. Then, all symmetries disappear when the amorphous precursor forms (which, however, may already contain crystal-like regions), and eventually the highly symmetric crystalline phase develops. So symmetry breaking during the crystallization of a liquid seems to be a complex process, in which the transition between two highly symmetric states happens via intermediate states of lower symmetry. Further experimental, numerical and theoretical work is still needed to merge these pieces of information into a unified picture of nucleation, in which structural analyses of the type performed by Tan et al.\(^\text{1}\) will certainly have their place.

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**PLANETARY SCIENCE**

**Subsurface air flow on Mars**

When the atmospheric surface pressure is just right, a temperature difference can drive a continuous flow of rarefied gas through the soil matrix — a previously unrecognized process on Mars.

Norbert Schörghofer

One of the peculiar facts about the martian atmosphere is that its molecular mean free path, on the order of 10 μm, is comparable to the size of dust grains. Up to now this was considered a mere nuisance that makes calculations of the flow or diffusion of gases through the porous soil a bit more complicated than it would otherwise be\(^\text{2,3}\). But, as reported in *Nature Physics*, Caroline de Beule and her collaborators exploit this property\(^1\). They show that it can result in a continuous gas flow with a force strong enough to move soil particles, based on the concept of a Knudsen pump — an exotic phenomenon from kinetic theory, which has been known for over a century\(^4,5\).

To understand this effect, it is useful to repeat the classical physical argument for thermal transpiration. Suppose that two containers, filled with the same gas, are connected by a tiny hole and are allowed to equilibrate to a steady state. If the mean free path is larger than the size of the opening, then the mechanical condition of equal pressure \(p\) on each side is replaced by a balance in gas flux, \(n v\), where \(n\) is the number density and \(v\) the mean molecular velocity along one direction. Combined with the ideal gas law and the fact that \(v\) increases with the square root of temperature, \(n v\) is proportional to \(p/\sqrt{T}\), which no longer represents a balance in pressure. When the containers are connected to large tubes, the pressure difference drives a continuous gas flow.

De Beule and co-authors tested their theoretical calculations for the martian surface by conducting an experiment that demonstrates its action in a 4 mbar atmosphere and a bed of dust-sized basalt grains, conditions that mimic the surface of Mars. To distinguish a Knudsen pump flux from buoyancy-driven thermal convection, they used a drop tower to carry out low gravity experiments, and observed the predicted gas flow. When the bed of dust is illuminated with a laser that causes a strong temperature gradient, dust particles are lifted off the surface.

The thermal transpiration flow is driven by strong temperature contrasts that are abundant on Mars. Owing to the tenuous atmosphere, any shadow boundary causes a significant horizontal temperature contrast. Figure 1 shows a temperature field derived from an infrared camera that orbits Mars. It illustrates the spatial heterogeneity in the shadow boundary of a highland region.