

## RANDOM ORGANIZATION

## Ordered chaos

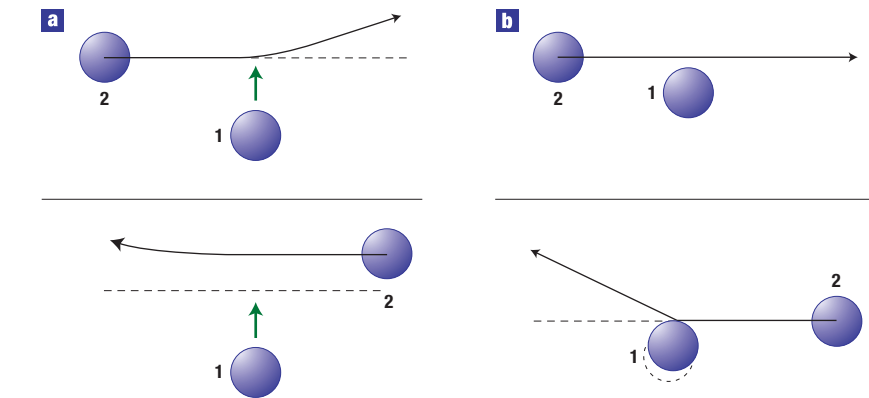
Although a driven colloidal suspension is not at equilibrium, a systematic study shows that such a system can still undergo a phase transition — albeit to a randomly organized state.

Daan Frenkel

is in the Department of Chemistry, University of Cambridge, Lensfield Road, Cambridge CB2 1EW, UK. e-mail: df246@cam.ac.uk

When we speak about self-organizing systems, we intuitively think of situations where an initially disordered state spontaneously evolves into an ordered one. On page 420 of this issue, Corté and co-workers present a combined numerical and experimental study<sup>1</sup> of a driven system of spherical particles dispersed in a viscous liquid. This system can self-organize in such a way that an unstable initial state transforms into a long-lived final state that shows none of the conventional signs of order (see also ref. 2). The authors refer to this process as the emergence of ‘random organization’. Interestingly, the simulations predict — and the experiments confirm — that this dynamical transition exhibits many of the characteristics of a continuous phase transition in a system at equilibrium. The work of Corté *et al.* is important because random organization is a very common phenomenon, yet in most cases it is impossible to carry out the kind of systematic comparison between experiment and theory that can be done in the case of colloidal model systems.

What distinguishes random organization from, say, ordering in an equilibrium phase transition? First of all, the systems that we discuss are not in equilibrium. For instance, in the case that Corté *et al.* studied, the system is subject to slow periodic shear. Normally, one would not expect a strongly driven system to be in a stationary state: when we prepare a cocktail by shaking (or even stirring), the distribution of ice cubes in the drink is different after every shake. Yet, when Corté *et al.* ‘shake’ their colloids — be it numerically or in a Couette cell — they find that, after an initial transient state, all particles oscillate around fixed (but otherwise random) positions; that is, unless the shear amplitude exceeds a critical threshold. Beyond that point, the random organization is lost: an increasing fraction of particles do not return to their initial



**Figure 1** Two ways in which time-reversibility can be broken in a periodically sheared, viscous suspension of large colloids. The figures show the trajectory due to periodic shear of a colloid **2** as seen by an observer fixed at the original position of colloid **1**. **a**, A conservative force acts between colloids **1** and **2** (indicated by a green arrow). This force deflects colloid **2** from its (dashed) streamline (upper panel) and the colloid does not return to its position (lower panel). **b**, The role of diffusion. In the first half of the cycle (upper panel), colloid **1** does not obstruct the path of colloid **2**. However, on the way back (lower panel) colloid **1** has diffused into the path of colloid **2**, and colloid **2** is deflected.

position after one cycle of the shear and the result is that the system behaves diffusively.

This transition from the organized to the diffusing state is sharp but it is preceded by clear ‘pre-critical’ phenomena; for instance, the time  $\tau$  that it takes for the system to settle down to its steady state diverges as the transition is approached (in the present case, as the shear amplitude  $\gamma$  approaches a critical value  $\gamma_c$ ). Corté *et al.* find that  $\tau \sim 1 / |\gamma - \gamma_c|^\nu$ , where, both for the model and the experiment, the exponent  $\nu$  is close to 4/3. The value of  $\nu$  depends on the dimensionality of the problem and on the nature of the underlying model. As there are many systems of great practical importance that undergo a random-organization transition it is important to know if and how relaxation times diverge in those systems on the approach to the threshold for random organization. In some cases (such as the spreading of epidemics or the changes in populations during evolution), the behaviour is known to be different from the case studied by Corté and co-workers (these phenomena are best described by so-called

directed-percolation models) but in other cases the analogy still needs to be explored.

In addition to the generic aspects of random, non-equilibrium organization there are also specific features of the system of sheared colloids that are of interest. As the equations of hydrodynamics at low Reynolds numbers are time-reversible (to be more precise: the velocities change sign when the external stresses do), we would always expect to observe random organization in a system of colloids that only interact through the intervening liquid. Any deviations from the state where all particles return exactly to their initial position after one cycle is therefore due to interactions that break the time reversibility. There are several candidate mechanisms: conservative (non-hydrodynamic) forces between the particles do not change sign when the imposed shear is reversed and can therefore destroy random organization (see Fig. 1a,b). Most likely, this mechanism is of key importance in the experiments of Corté *et al.* However, in addition, a small amount of diffusion of the (very large) colloids can also break time

reversibility, as colloids that barely avoid each other when the shear is increased may have diffused onto a collision course on the way back (Fig. 1c,d). It is clear that in both cases, the onset of diffusive motion acts as a macroscopic indicator of something that happens on very short length scales: the system acts like a 'random' force microscope but it is not clear what it 'sees'. We do not know what microscopic information can be extracted from the experiments. However, the fact that the system exhibits critical behaviour at the onset of random organization suggests that much of the microscopic detail is irrelevant for the macroscopic behaviour.

There is another question that the present experiments raise: how random is the state of random organization? If we use the simple model of Corté *et al.* then the effect of periodic shear is to move particles along a horizontal line parallel to the direction of shear. Particles that, due to this shearing motion, come within a certain threshold distance from another particle will be kicked off course. The implication is that the state of random organization does have considerable local order. In fact, highly ordered ('crystalline') arrangements of the particles might yield structures that are stable even at arbitrarily large shear values. However, as Corté *et al.* argue, these states are

very improbable and cannot be found in a normal experiment.

It is clear that the present study calls for a much more extensive investigation of the emergence and breakdown of random organization, not just in dispersions (or emulsions), but also in complex (for example, biological) systems. The relevance of such studies may well extend beyond physics, as the society that we live in could arguably be described as a state of random organization.

#### References

1. Corté, L., Chaikin, P. M., Gollub, J. P. & Pine, D. J. *Nature Phys.* **4**, 420–424 (2008).
2. Pine, D. J., Gollub, J. P., Brady, J. F. & Leshansky, A. M. *Nature* **438**, 997–1000 (2005).

## CAVITY QED

# Signs of anharmonicity

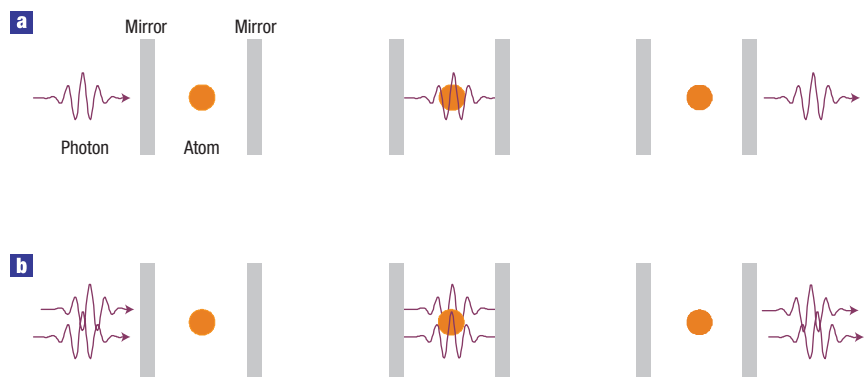
The energy of an atom binding one photon in a cavity can be derived classically. But when two photons are bound to the atom, signatures of light quantization appear in the spectrum. These have now been observed in the optical domain.

### Howard Carmichael

is in the Department of Physics, University of Auckland, Private Bag 92019, Auckland 1142, New Zealand.

e-mail: h.carmichael@auckland.ac.nz

A single photon confined to an optical cavity that is sufficiently small produces an electric field comparable to that of a standard household electrical socket. The field is strong enough to shift the energy levels of an atom trapped in the cavity by more than its emission linewidth, thus observably changing the frequencies at which light is absorbed and emitted. In the process the photon becomes bound to the atom, forming in effect an atom–photon 'molecule'. Strictly, atomic energy levels are not merely shifted then, but a new object is formed, with energy different from the sum of its parts. Though intrinsically quantum mechanical, the binding of just one photon to an atom has a classical analogue: the binding energy,  $e_b$ , can be derived from the classical mechanics of coupled harmonic oscillators (one modelling the photon in the cavity and the other the atom). The binding energies of two, three and more photons, however, carry a direct signature of the quantization of light, as it is larger by a factor depending on photon number:  $\sqrt{2}e_b$ ,  $\sqrt{3}e_b$ , and so on. Observing this dependence on photon number spectroscopically has long been a goal of cavity quantum electrodynamics.



**Figure 1** Frequency by number. **a,b**, Photons injected by a weak laser beam (left) bind to an atom in a cavity (centre) and the 'molecule' so formed decays (right). Depending upon their frequency, photons either bind singly (**a**) or in pairs (**b**). The resonance frequency for single binding is determined by the (classical) mechanics of coupled harmonic oscillators; that for pair binding is predicted correctly only by quantum mechanics.

In a clever experiment that combines a tiny optical cavity with techniques for cooling and trapping neutral atoms, Ingrid Schuster *et al.*<sup>1</sup> have done just that. As reported on page 382 of this issue, they looked at the scattering of weak laser light by an optical cavity containing one atom, and detected a resonance that arises from the binding of a pair of photons to the atom (see Fig. 1).

Calculating the quantum mechanically allowed energies of a fixed number of photons interacting near resonance with one atom in a cavity is a standard exercise

in quantum optics; it is a problem assigned to students. Observing consequences of the calculated energies in experiments is a far more difficult task, primarily because the discrete energy levels obtained are smeared out in practice by spontaneous emission from the atom and photon loss at the cavity mirrors. Only if binding energies separate the energy levels by more than the smearing can resonances associated with the binding of a definite number of photons to the atom be resolved. The binding of one photon produces a spectroscopic doublet (the so-called