having arisen in an ancient, shallow, marine environment, on the basis of the textures of interlayered sediments and the distribution patterns of rare-earth elements. Such patterns have previously been interpreted to indicate the deposition of carbonate minerals from seawater[9]. The entire region in which these rocks are located was previously found to be metamorphosed rock that had been subjected to high temperature and pressure[10]. In the Australian rocks with ancient stromatolites[2], laminations are clearly visible; in the Greenland samples, however, the proposed laminations are less clear, and the degree of metamorphism is higher than that of the Australian rocks.

The lack of unambiguous, well-preserved laminated structures would preclude the identification of any intricate original textures that might indicate biological input to the structure. However, Nutman *et al*. identified remnant laminations and conical stromatolite-like shapes that they consistently interpreted as being microbially generated structures. Apart from these conical shapes, Nutman and co-workers also identified some dome-like shapes of proposed stromatolites. However, they did not find the diversity of stromatolite forms described in the Australian study. With few specimens, and a complex history of rock metamorphism, this raised the question of whether non-biological processes might have generated the dome-like and conical shapes in these ancient Greenland rocks.

Allwood *et al*. argue that the stromatolite-like shapes observed at the Greenland site arise from rock deformation. When they compared the front and side profiles of rock samples that contained stromatolite-like structures, they noted that one side shows a compressional deformation whereas the other shows an extensional deformation. This indicates that the structures are not stromatolite cones, but elongated ridges (Fig. 1b). Furthermore, the folding direction of the stromatolite ridges is parallel to the orientation of pressure-induced mineral textures on smaller scales in the same rock. These observations provide strong evidence for physical rock deformation and therefore offer a non-biological explanation for the observed structures.

In addition, Allwood and colleagues argue that the rock itself did not form in a shallow marine setting, but instead arose when carbonate minerals crystallized from fluids that circulated through an existing rock. If this is true, the observed dome-like and conical structures are definitely not stromatolites. Allwood *et al*. used a trace-element analysis technique that has high spatial resolution to show that the internal laminations in the conical structures represent the specific replacement of a type of silicate rock by fluid-derived carbonate minerals. The authors found that the rare-earth-element signal associated with the presence of seawater seems to be mainly concentrated in mica minerals in the rock, but is also present in the carbonate areas. Allwood and co-workers suggest that this is possible if the fluids from which the minerals crystallized during later stages of the rock's existence ultimately derived from seawater as well. So although Nutman *et al*.[1] and Allwood *et al*.[2] report similar patterns of rare-earth elements in the rocks, they offer diverging interpretations of what these patterns mean. This highlights the complexities in discerning primary chemical signatures in such highly deformed rocks.

The biological input to ancient stromatolites is a long-standing controversy. The rocky outcrop on Greenland has not been discovered for long, and few researchers have studied this rock in relation to its geological surroundings. Future research might lead to a firm understanding of the primary versus secondary processes that shaped this rock. Clearly, the work of both Nutman *et al*. and Allwood *et al*. will form the basis for the interpretation of other possible stromatolites in the ancient rock record. ■

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1. Nutman, A. P., Bennett, V. C., Friend, C. R. L., Van Kranendonk, M. J. & Chivas, A. R. *Nature* **537**, 535–538 (2016).
2. Allwood, A. C., Walter, M. R., Kamber, B. S., Marshall, C. P. & Burch, I. W. *Nature* **441**, 714–718 (2006).
3. Allwood, A. C., Rosing, M. T., Flannery, D. T., Hurowitz, J. A. & Heirwegh, C. M. *Nature* **563**, 241–244 (2018).
4. Walter, M. R. (ed.) *Stromatolites. Developments in Sedimentology 20* (Elsevier, 1976).
5. Grotzinger, J. P. & Rothman, D. H. *Nature* **383**, 423–425 (1996).
6. Pope, M. C., Grotzinger, J. P. & Schreiber, B. C. *J. Sediment. Res.* **70**, 1139–1151 (2000).
7. Grotzinger, J. P. & Knoll, A. H. *Annu. Rev. Earth Planet. Sci.* **27**, 313–358 (1999).
8. Bosak, T. *et al. Geobiology* **10**, 384–401 (2012).
9. Bolhar, R., Kamber, B. S., Moorbath, S., Fedo, C. M. & Whitehouse, M. J. *Earth Planet. Sci. Lett.* **222**, 43–60 (2004).
10. Boak, J. L. & Dymek, R. F. *Earth Planet. Sci. Lett.* **59**, 155–176 (1982).

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QUANTUM PHYSICS

Quenching our thirst for universality

Understanding the dynamics of quantum systems far from equilibrium is one of the most pressing issues in physics. Three experiments based on ultracold atomic systems provide a major step forward. See Letters p.217, p.221 & p.225

MICHAEL KOLODRUBETZ

Although we live in a world of constant motion, physicists have focused largely on systems in or near equilibrium. In the past few decades, interest in non-equilibrium systems has increased, spurred by developments that are taking quantum mechanics from fundamental science to practical technology. Physicists are therefore tasked with an important question: what organizing principles do non-equilibrium quantum systems obey? On pages 217, 221 and 225, respectively, Prüfer *et al.*[1], Eigen *et al.*[2] and Erne *et al.*[3] report experiments that provide a partial answer to this question. The studies show, for the first time, that ultracold atomic systems far from equilibrium exhibit universality, in which measurable experimental properties become independent of microscopic details.

The researchers use low-density gases of rubidium[1,3] or potassium[2] atoms that are cooled to temperatures close to absolute zero. At sufficiently low temperatures, these atoms begin to show quantum-mechanical behaviour, forming a macroscopic quantum state known as a Bose–Einstein condensate. Starting from either such a condensate[1,2] or an uncondensed gas[3], the researchers rapidly change experimental parameters — a process known as a quench. Rather like a cartoon character that looks down to discover they have accidentally run off a cliff, the quench initiates far-from-equilibrium dynamics.

Such quenches are relatively easy to realize, but what the researchers see next is surprising. Consider all the variables that can be associated with a given experiment: power fluctuations of lasers, variations in the lab's temperature, microscopic details of atomic interactions, and so on. The researchers find that the dynamics of their experiments, despite involving strongly interacting atoms far from equilibrium, become independent of these variables.

Eigen *et al.* accomplish this universality by carefully eliminating all but two of the variables in their experiment: the density of the atomic gas and the scattering length. The latter describes how closely two atoms can pass without interacting. The authors then go one step further and eliminate the dependence of the scattering length on variables in a clever way.

First, to prepare the initial condensate, the authors set the scattering length to zero — they 'turn off' the interactions — using a magnetic field[4]. Second, they quench the scattering length to infinity, again using the magnetic field. If we consider increasing the density of the gas by, for example, a factor of eight, the spacing between the atoms decreases by a factor of two. Zooming in (rescaling) by this factor of two, the atomic system looks exactly the same as it did before the density was increased, because the scattering lengths of zero and infinity are unchanged.

Eigen and colleagues vary the density of the gas by a factor of about ten, and observe that the experimental dynamics are independent of the density after rescaling both space and time. They also adjust the temperature of the gas and show that universality holds when one more variable is considered — namely, the length scale on which the gas exhibits quantum-mechanical behaviour.

Prüfer *et al.* and Erne *et al.* uncover a different form of universality. On the face of it, the experiments of these two groups are wildly different. Erne and colleagues start with a three-dimensional gas, quench to one dimension, and observe the density of the gas as a function of position and time. Prüfer and colleagues work in one dimension throughout, explore the internal states (spins) of the atoms and carry out a quench that allows these spins to fluctuate. But, after a short time, both groups observe universality, which they argue results from a phenomenon called a non-thermal fixed point.

For systems in equilibrium, the concept of a fixed point comes from one of the great discoveries of twentieth-century physics, known as the renormalization group. This framework studies how a system evolves as we zoom out from the microscopic to the macroscopic scale, and successfully describes the emergence of key phases of matter such as magnetism. Fixed points are states of a system that remain unchanged on zooming out. Non-thermal fixed points occur when non-equilibrium systems approach such a state, with the role of zooming out played by the passage of time[5].

A classic example of a non-thermal fixed point is wave turbulence, in which the energy of waves is transferred from large to small scales. Prüfer *et al.* and Erne *et al.* demonstrate the first examples of universality caused by non-thermal fixed points in systems dominated by quantum mechanics. Like Eigen and colleagues, the groups show that their results are robust by widely varying the initial conditions of their experiments and observing that the dynamics are effectively unchanged.

Although Prüfer *et al.* and Erne *et al.* use different quenches and measure different properties, their results are remarkably similar. This resemblance provides perhaps the best evidence for the existence of universality in these atomic systems. At a technical level, the experiments do differ in their critical exponents (numbers that describe the properties of fixed points), which indicates that the two fixed points are different.

Together, these three studies provide a substantial step forward in our understanding of quantum systems far from equilibrium. However, a complete picture of the underlying universality remains to be determined. A notable concern for all of the experiments is that the universality occurs over limited time and length scales. Longer times, in particular, would probably be required to realize non-equilibrium steady states that are useful for practical applications. By analogy with wave turbulence, one possibility for extending the reach of the universality could involve continuously pumping energy into the systems; it is well documented that universality is, at best, transient in the absence of an external drive.

From a fundamental perspective, these experiments pave the way for exploring a wide range of theoretical and experimental questions regarding non-equilibrium universality. For example, what are the possible classes of non-thermal fixed points? What happens at extremely high or low energy scales, at which the universality breaks down? And under what conditions does universality arise in generic quenched systems? These are challenging questions to answer, but I, for one, hope that these experiments open the door to placing non-equilibrium quantum systems alongside equilibrium ones in the lexicon of modern physics. ■

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1. Prüfer, M. *et al. Nature* **563**, 217–220 (2018).
2. Eigen, C. *et al. Nature* **563**, 221–224 (2018).
3. Erne, S., Bücker, R., Gasenzer, T., Berges, J. & Schmiedmayer, J. *Nature* **563**, 225–229 (2018).
4. Chin, C., Grimm, R., Julienne, P. & Tiesinga, E. *Rev. Mod. Phys.* **82**, 1225–1286 (2010).
5. Orioli, A. P., Boguslavski, K. & Berges, J. *Phys. Rev. D* **92**, 025041 (2015).

BIOPHYSICS

Cellular stretch reveals superelastic powers

External forces can make cells undergo large, irreversible deformations. It emerges that stretched mammalian cells grown *in vitro* can enter a state called superelasticity, in which large, reversible deformations occur. **SEE ARTICLE P.203**

MANUEL THÉRY & ATEF ASNACIOS

In Rudyard Kipling's classic children's bedtime story[1], the elephant's elongated trunk arose because a crocodile grabbed "and pulled, and pulled, and pulled" on the nose of an elephant's child. The elephant's child escaped, but waited in vain for its nose to shrink back to normal. This scenario of an irreversible extension mirrors what happens in the laboratory when cells that are subject to external tension undergo major deformation. However, *Nature*, Latorre *et al.*[2] report on page 203 that mammalian epithelial cells grown *in vitro* can, unexpectedly, demonstrate a mode of reversible, large-scale shape changes — a property termed superelasticity.

When our skin gets cut, it breaks apart at the wound site. This is because the surface of skin, like that of most organs, is subjected to tension. This tension helps to limit the size and sculpt the shape of organs. Moreover, a cell can both generate and resist tension. In the cytoplasm, there are fibre-like elements of the cell's structural 'skeleton', called cytoskeletal filaments, that can transmit force. The type of cytoskeletal filaments that form from the protein actin can be moved by myosin proteins to generate the contractile forces that regulate cell shape. Adhesion sites that join cells together can relay this force between cells and cause tension to build up throughout an entire tissue[3]. However, cells under tension do not usually tear apart, because their material properties enable them to resist this tension[4,5].

If cells under tension undergo small-scale deformations, the resulting changes are mainly elastic[6], and a linear relationship exists between an increase in tension and an increase in deformation[7,8]. But in large-scale deformations, cells can enter a state termed plasticity, in which the breakage of bonds between cytoskeletal filaments leads to irreversible deformations that prevent full cellular recovery, even if the associated stress is released[9]. Latorre and colleagues describe a mechanism whereby cells under tension that undergo large-scale deformations change from being in an elastic state to enter a regime in which the cells elongate without requiring an increase in tension. Moreover, these deformations are reversible, indicating that cells can shift from an elastic state to what is called a superelastic state, and