open and/or prevent back-slippage, allowing forward movement of pre-protein segments by Brownian motion. Detailed kinetic assays will be necessary to discriminate between these possibilities.

To visualize the channel–motor complex, Zimmer *et al.*[3] had to immobilize it in a crystal lattice. Consequently, they could capture the structure of only one of its possible states — much like a party snapshot freezes a single move on the dance floor. Synthesis of the full spectrum of channel and/or motor motions will necessitate more snapshots. Tsukazaki *et al.*[5] present one such additional picture on page 988, revealing a different conformational state of the SecY channel.

In these authors' structure, the motor is absent. Instead, they used an antibody to hold a single SecY channel in a particular state. The antibody binds specifically to a motor-binding site and freezes the channel in what is proposed to be a 'pre-open' state. This conformation exposes a cleft with access to the cytoplasm, which Tsukazaki and colleagues hypothesize[5] could attract signal peptides. Whether these antibody-driven effects faithfully mimic those driven by the binding of the motor is unknown. Nevertheless, they reveal the inherent repertoire of potential channel motions.

Like Erlandson and colleagues[4], Tsukazaki *et al.* also used cysteine cross-links to study a functional complex of the channel with the motor. These experiments revealed that a region of the motor undergoes significant conformational changes when it binds to the channel. These interactions probably involve the second copy of the channel, which is absent from Zimmer and colleagues' channel–motor structure. This second copy is thought[1] to act as a docking station for the engine part of the motor.

The implications of these channel–motor 'kiss-and-tell' structures for understanding the mechanics of pre-protein translocation are important. A possible pathway for the pre-protein to follow has now been coarsely charted. The range of possible channel conformations and the motions of the motor's domains can now be predicted and tested. A second copy of the motor is apparently not required for interaction with a single translocating channel. Similarly, the remarkable ATP-driven motions of the motor's hands that accompany protein secretion[10] need not lead to profound membrane penetration of the motor. But to confirm these and other conclusions, experimentally less disruptive isolation of the complexes in a functional form and freezing of other conformational states will be necessary.

Solving structures of membrane proteins is not a trivial pursuit. As we contemplate in awe the reported achievements[3-5], a wish list of future findings comes to mind: higher resolution structures of the twin channel–motor complex, accompanied by a trapped pre-protein chain; understanding how the motor recognizes pre-proteins and how it converts the chemical energy of ATP into mechanical work; and determining the dynamics of this astonishing cellular nanomachine. ■

Anastassios Economou is at the Institute of Molecular Biology and Biotechnology, Foundation of Research and Technology-Hellas, and in the Department of Biology, University of Crete, PO Box 1385, Iraklio, Crete, Greece.
e-mail: aeconomo@imbb.forth.gr

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CONDENSED-MATTER PHYSICS

Surviving the transition

Kristian Helmerson

Observations of the birth of a superfluid have uncovered details of the microphysics of phase transitions. Whether these results can be used to model such transitions in the early Universe is an open question.

The spontaneous formation of topological defects — stable configurations of matter — is thought to accompany most continuous, non-equilibrium phase transitions in condensed-matter physics. But the study of the microscopic dynamics underlying the formation of such defects is a challenge, especially in superfluid transitions. On page 948 of this issue, Weiler *et al.*[1] report observations of topological defect formation in a particularly helpful superfluid phase transition — the Bose–Einstein condensate (BEC) transition— in a trapped gas of rubidium atoms. These observations offer unique insights into the microscopic physics of phase transitions.

Approximately 10^{-35} seconds after the Big Bang, the Universe underwent a phase transition resulting from the cooling associated with its rapid expansion. We generally think of a phase transition driven by cooling as one that takes a system from a disordered state to an ordered one — for example, water turning into ice. Yet the Universe is not an ordered state, but is filled with galaxies, stars and other celestial bodies. A way out of this dilemma was proposed by Thomas Kibble[2,3] in 1976. He argued that, as the Universe cooled and approached the phase transition, large fluctuations in the vacuum in the form of topological defects, such as cosmic strings, were formed. These defects, which persisted even after the transition, eventually led to the formation of larger structures in the Universe.

The key to the survival of these topological defects is that they are formed locally on a timescale that is shorter than the time it would take light to propagate from the location of one defect to another; hence the defects would not be able to know about one another. In the parlance of physics, this means that the formation of the defects is not causally connected. Using similar reasoning, Wojciech Zurek suggested[4,5] that in a condensed-matter system, a second-order phase transition — in which the transition between the old and the new phase is continuous — could result in defect formation if the transition is crossed rapidly enough.

Zurek went on to propose a specific experiment involving the phase transition of liquid helium ^{4}He, at a temperature of 2.17 Kelvin, from a normal fluid to a superfluid; that is, a fluid with no viscosity. If the helium could be cooled rapidly enough, then topological defects in the form of quantized vortices would be produced. In this case, however, the timescale for the causal connection of the defects is not determined by the speed of light but by the speed of sound in the bulk superfluid.

Since Zurek's suggestion, the mode of formation of topological defects, which is known as the Kibble–Zurek mechanism, has been observed in liquid crystals, arrays of superconducting Josephson junctions, nonlinear optical systems, fluid convection systems and superfluid ^{3}He. But, surprisingly, it has not been observed in ^{4}He, the quintessential superfluid and the system referred to in Zurek's original proposal. Weiler *et al.*[1] now report observing such defects in a BEC transition of a trapped atomic gas.

In their experiments, Weiler *et al.* evaporatively cooled a gas of weakly interacting rubidium (^{87}Rb) atoms confined in a magnetic trap. Evaporative cooling normally occurs slowly, such that the system being cooled is close to reaching thermal equilibrium. This is similar to what occurs when the hottest (highest-energy) molecules evaporate from a cup of coffee and the rest of the coffee 're-thermalizes' — that is, comes back to thermal equilibrium — at a lower temperature. The system can, however, be thrown out of equilibrium by rapidly modifying the energy distribution. Weiler *et al.* achieved this by using radio-frequency transitions that selectively remove a substantial fraction of the highest-energy atoms from the magnetic trap. This technique was first used[6] to study the formation dynamics of a BEC.

Weiler and colleagues found a regime in which the gas of rubidium atoms can rethermalize locally on a timescale faster than it would take for atoms on one side of the magnetic trap to let atoms on the other side know what is going on. As a result, a local mini-BEC could form in one place in the trap while another mini-BEC formed elsewhere. Because these mini-BECs (typically referred to as quasi-condensates) do not know about each other, they will each have a quantum-mechanical phase that is independent of one another. When three such mini-BECs with independent phases merge, they can form a vortex, as an earlier experiment[7] showed.

A more formal description of the process of vortex formation would characterize the size of the quasi-condensates by the coherence length, ξ (the spatial extent over which the phase is uniform). If the phase transition is approached while the system is close to thermal equilibrium, ξ diverges at the critical point of the phase transition and there is no length scale for quasi-condensate formation. Thus, no topological defects are expected. But if the critical point is crossed rapidly enough, then the coherence length just before crossing the transition is frozen in, and quasi-condensates of coherence length ξ can form, which, for a big enough system, would lead to the formation of topological defects.

Although the experiments of Weiler *et al.* support the mechanism of Kibble and Zurek, the finite size of the system limits the observation of universal scaling laws, such as the density of defect formation, which should increase as $1/\xi^2$. However, given that non-equilibrium phase transitions have important consequences, as exemplified by the Kibble–Zurek mechanism, these experiments are a welcome addition. Such experiments[1,8] show that trapped atomic gases provide a system in which the microscopic dynamics underlying the important mechanisms in a non-equilibrium phase transition can be probed, understood and controlled. Whether they can be used to model the early evolution of the Universe remains to be seen, but they look promising for providing new insights into these, traditionally difficult to study, phase transitions. ■

Kristian Helmerson is at the National Institute of Standards and Technology, Gaithersburg, Maryland 20899-8424, USA.
e-mail: kristian.helmerson@nist.gov

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EARTH SCIENCE

Deducing a reducing mantle

William F. McDonough

Increasingly sophisticated techniques are being used to persuade ancient rocks to yield information about conditions on and in the early Earth — for instance, about the oxidation state of the mantle.

They say that a picture is worth a thousand words. In science, one datum point can be worth a thousand models. On page 960 of this issue, Berry *et al.*[1] report the first results obtained by applying a new approach to estimating the oxidation–reduction (redox) condition of Earth's upper mantle during the Archaean, some 2,700 million years ago. Their study is based on the ratio of different oxidized states of iron (Fe^{3+} to Fe^{2+}) in inclusions of ancient komatiite rock, trapped in crystals preserved in ancient lava flows in Zimbabwe. The crystals should have protected the inclusions from subsequent alteration, which should thus reflect the native lava state.

Berry and colleagues' findings are groundbreaking, both for the experimental method they used (X-ray absorption near-edge structure spectroscopy, which shows that we can interrogate minute and precious fragments of the ancient Earth), and for what the findings reveal about the early Earth. They will embolden others to analyse rare recorders of ancient and remote redox conditions, such as ancient zircons and other minerals, early Solar System condensates in meteorites, and inclusions in diamonds. And they have implications for several aspects of our understanding of Earth's history: the secular evolution of mantle oxidation state; oxidation of the atmosphere; melting conditions for the formation of the ancient lavas; and the nature of the tectonic environment in which these lavas formed.

When, around 2,700 million years ago, the lavas erupted on the Earth's surface, the atmosphere was low in oxygen, and the circumstances that first produced an oxygenated atmosphere (the 'great oxidation event') were still 500 million years off. Ever since the first conjectures about the great oxygenation event[2,3], authors have speculated as to whether the mantle was the source of the oxygen. But the redox conditions of the mantle today do not necessarily reflect those in the early Earth because of the degassing, magmatism, cycling of tectonic plates and mantle convection that have occurred during the past 2,700 million years.

The komatiitic melt inclusions studied by Berry *et al.*[1] have low concentrations of Fe^{3+} (that is, a high degree of reduction and low oxidation), which the authors interpret as reflecting the redox state of the host lavas. That state is comparable to the redox state of the mantle source from which the continents are formed — basalt rocks produced at mid-ocean ridges, where tectonic plates are diverging. These rocks have the most highly reduced condition recorded for major outpourings of basaltic magmas, as compared with other tectonic settings (for example convergent boundaries, where one plate is being thrust beneath another, or where volcanic activity is occurring within a plate).

Today, basalts from convergent, Andean-type margins, which include those from the Pacific's ring of fire, are the most highly oxidized, and this is thought to be due to the addition of water transported along with the down-going, subducted plate to the site of magma generation. Basalts from intraplate settings, such as those beneath Hawaii, have intermediate water content and a transitional oxidation state between those of basalts from Andean margins and from mid-ocean ridges. Berry and colleagues show that their komatiite melt inclusions are not significantly water-bearing. Thus, the low Fe^{3+} and low water content of the inclusions are consistent with komatiite genesis through large-scale melting of the mantle under relatively anhydrous, high-temperature conditions[4,5].

Because these ancient, Archaean melt fragments record such a reduced oxidation state for iron, one comparable to that of the dominant volume of mantle today, the implication is that the mantle is unlikely to have provided the atmosphere's oxygen in the past. It is not impossible that it did; but such an outcome would have required exceptional circumstances.

The early mantle was hotter and more active than it is today, as evidenced by the presence of komatiites (such high-temperature melts are limited to Earth's first 2,500 million years or so); the higher content of heat-producing radioactive elements; and the greater impact flux of asteroids in the first thousand million years of Solar System history. Thus, mantle convection was more vigorous in the early Earth, which probably led to a more homogeneous mantle, one less capable of storing unprocessed, more-oxidized material. Given this hot, active, early Earth, the findings of Berry *et al.* point to a mantle that became more oxidized, not more reduced, with time. This in turn could indicate that the process of recycling oceanic plates back into the mantle perhaps contributed to the progressive oxidation of part of the mantle through time.

The tectonic context for komatiite genesis continues to be a puzzle. Berry and colleagues' results, coupled with an earlier trace-element study on similar melt inclusions from these lavas[6], reveal that these high-temperature melts are more akin to modern lavas from a divergent