trenches at the ocean margins, where it returns to Earth's deep interior in a process known as subduction. The continents, although they drift and deform in response to the plate movements, are largely spectators in the recycling of the surface. The continental geological record dates back all the way to the Archaean, whereas almost all the oceanic record that is more than 200 million years old has been subducted and lost. Plate tectonics explains how Earth works today, but has it always been this way? Did plate tectonics begin only in the mid-Archaean, as Moore and Webb's model requires? Looking to the continental geological record for answers, we find plenty of room for debate.

Certainly, many have argued that the geology of the early Archaean Earth is reminiscent of current conditions on Venus or on Jupiter's moon Io. These are dominated by volcanic processes from below, with little horizontal motion[2,3], in agreement with the authors' model (Fig. 1). Others have claimed, from a theoretical point of view, that plate tectonics works very differently in a hot Earth and may not be viable because hotter oceanic plates are too buoyant to subduct[4], or because stresses in a hot Earth are much lower and it is less likely that the surface could be broken up into plates[5].

Proponents of early plate tectonics during the first half of the Archaean point out that the Archaean paradox is quite easy to resolve if the oceanic plates simply recycle faster in a hotter Earth[6,7]. There are magmatic rocks from the Archaean that are similar to those found in present-day subduction zones, as well as structures imaged in the ancient crust that look as though they could have been created by subduction. Furthermore, recent theoretical models paint a more optimistic picture of the viability of subduction in a hotter planet[8].

Moore and Webb's work is sure to re-energize this debate because they use the Archaean paradox to argue against early plate tectonics and their theoretical models produce plates in the late Archaean. Their simple model is elegant because it contains a pre-plate, heat-pipe Earth that undergoes a predictable transition to a plate-tectonic Earth as a consequence of cooling through time. In the study of Earth-like extrasolar planets, there is a fierce dispute over whether plate tectonics is a common phenomenon or unique to our planet[9]. Quantifying how plate tectonics can evolve on planets of different sizes and compositions is an important contribution to this wider debate.

In their model, which so far is limited to small-scale, two-dimensional, flat-Earth simulations, the transition from a pre-plate, heat-pipe Earth to a plate-tectonic one is sudden and global. In reality, Earth is large enough for regional differences in the internal temperature to have been quite common even during major plate reorganization events[10], so it might be possible for the two modes to coexist for some time. It will also be interesting to see whether the wild fluctuations in the global rate of volcanic eruption that are present in simple, flat-Earth models also occur in more realistic models. ■

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CONDENSED-MATTER PHYSICS

Rotating molecules as quantum magnets

The push to engineer and probe quantum many-body systems using ultracold gases has reached a milestone with the observation of controlled dynamics caused by interactions between distant molecules trapped in a lattice. SEE LETTER P.521

ANDREW J. DALEY

Experiments with ultracold gases of atoms and molecules open up many avenues for exploring fundamental questions of many-body physics, because they offer a high level of control over the trapping potentials that confine the gases and interparticle interactions[1]. On page 521 of this issue, Yan and colleagues[2] provide a highly anticipated demonstration of a new system in this context, with potassium–rubidium molecules trapped in separate sites of an optical lattice formed by standing waves of laser light*. They observe the dynamics caused by dipolar interactions between distant molecules, setting the stage for the exploration of many-body phenomena and quantum phases of matter, especially those described by quantum spin models[3–6].

In Yan and colleagues' experiment, gases of potassium and rubidium at nanokelvin temperatures are associated to form K–Rb molecules by means of a magnetic-field ramp, and are then placed in the lowest-energy state of their electronic, vibrational and rotational degrees of freedom using laser-induced transitions. Ultracold gases of such heteronuclear ground-state molecules were first produced in 2008 (ref. 7), and are particularly interesting for the study of many-body physics because of the strong electric dipole moments exhibited by the molecules (0.57 debye units for K–Rb)[3,6].

But the authors have now gone a step further, introducing an optical lattice that traps molecules at individual lattice sites (Fig. 1), separated by 0.5 micrometres, in which the lifetime of the molecular gas (limited by heating processes) is 25 seconds. This allows the realization of models in which the translational motion of the molecules is frozen and the dynamics are dominated by the molecules' internal motion. The molecules can each be treated as effective spin-1/2 systems by identifying two different states of their rotational motion as spin up and spin down. Applying microwave fields to couple the rotational states allows the dipole–dipole molecular interaction to exchange angular momentum between spatially separated molecules, giving rise to effective interactions between the spins.

Yan *et al.* measured the effects of these interactions on dynamics using a Ramsey spectroscopy technique, in which the rotation of the molecules is controlled through microwave pulses. The interactions show up as oscillations of the system's collective spin state, with a dominant oscillation frequency that is characteristic of the dipole–dipole interactions between molecules in neighbouring lattice sites. The authors also demonstrate how the effects of pairwise interactions can be cancelled using multiple microwave pulses, leaving a general damping of oscillations in the collective spin state that is caused by interactions between many molecules.

These measurements highlight the two key advantages of loading molecules into an

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*This article and the paper under discussion[2] were published online on 18 September 2013.

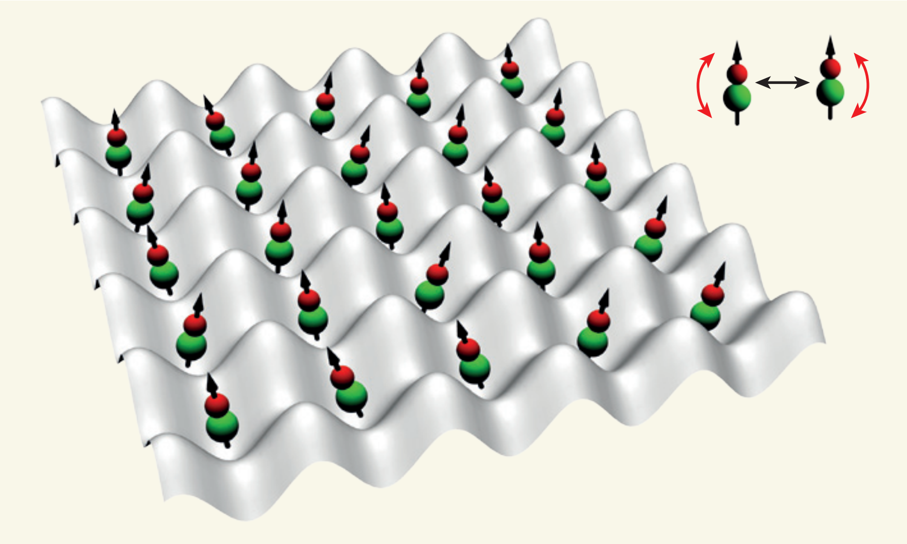

Figure 1 | Trapped in a lattice. Yan *et al.*[2] demonstrate a system of ultracold heteronuclear molecules (red and green) in an optical lattice (grey) that can be used to study quantum spin models. The lattice freezes the translational motion of the molecules, and a dipole–dipole interaction between molecules (dipoles shown as thick black arrows) couples different states of their rotational motion (red arrows), which can be used to represent quantum-mechanical spins. The authors' system currently has a smaller filling fraction of molecules than is shown here.

optical lattice. First, because the translational motion is frozen, the effective temperature in the rotational motion — and therefore the spin systems — can be very low, even if the initial temperature of the gas would have been too high to observe the dynamics cleanly. Second, trapping molecules in individual sites prevents collisions between molecules. In the case of K–Rb, collisions would lead to chemical reactions that produce K_2 and Rb_2 dimers[8]. This reaction releases a lot of energy, normally leading to the loss of molecules from the system.

Yan and colleagues also showed that when the molecules are allowed to move through the lattice, tunnelling weakly from site to site, their loss is further suppressed by a quantum-mechanical phenomenon known as the continuous quantum Zeno effect. In this mechanism, a dissipative process (the reactive loss) suppresses a coherent one (in this case, the tunnelling), so that the rapid loss of molecules from the same site actually decreases the likelihood that a molecule will move to a lattice site where another molecule is already present. Thus, counter-intuitively, a rapid loss process slows down the loss of molecules. Such suppression has previously been observed[9] for highly excited molecules of Rb_2, but it has now been observed cleanly for the first time in ground-state molecules.

This experimental system has been anticipated by many theoretical proposals, which have demonstrated that many classes of spin model can be realized by tailoring the dipole–dipole interactions with external electric and microwave fields[3–6]. This includes spin models that describe topological quantum phases[4]. Such exotic phases do not fit into the standard Landau theory that characterizes phase transitions with a local-order parameter — they are instead identified by highly non-local topological properties. As shown by Yan *et al.*, these systems are particularly suitable for the study of non-equilibrium dynamics in strongly interacting spin models. Although some spin models can be implemented with atoms in optical lattices[1], the interactions in those systems are limited to contact interactions when the atoms collide, and effective spin–spin interactions involve tunnelling of particles in the lattice. Dipolar molecular systems such as those of Yan and colleagues provide a means to create spin models with stronger interactions, allowing phenomena to be observed at much higher temperatures than those required in atomic systems.

At present, the biggest challenge in the K–Rb experiment is to increase the 'filling fraction' (the proportion of lattice sites occupied by a molecule), which is currently around 10%. This should ideally be close to 100% to realize some of the most interesting many-body models, which will require the production of molecular gases with higher initial density and at a lower temperature than achieved here. In the meantime, however, Yan and colleagues' work immediately opens the door to the study of dynamics in disordered spin models, with the randomness arising from the distribution of molecules in the lattice. As technical improvements are made over the next few years, this system will provide an exciting path for the realization of exotic many-body physics. ■

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CELL BIOLOGY

A table for two

Autophagy, the process of cellular self-cannibalism, comes in various forms. It now emerges that two of these — mitophagy and xenophagy — share a common initiator protein, Parkin. SEE ARTICLE P.512

MARCEL A. BEHR & ERWIN SCHURR

Infectious disease is not the inevitable consequence of exposure to a pathogen. Host factors have a crucial role in determining the outcome of such exposure, yet much remains unknown about how individuals vary in their capacity to resist pathogens. In this regard, genomic studies offer a tenable approach to identifying pathways involved in microbial handling. An intriguing example of how genomic findings can guide the mechanistic understanding of complex biological systems is Manzanillo and colleagues' paper[1] on page 512 of this issue. The study concerns the mechanism by which cells remove the human pathogen *Mycobacterium tuberculosis* through a process called autophagy*.

Genomic studies provide lists of genes, both expected and unexpected. Whereas expected genes serve to reinforce existing models, it is the set of genes with no apparent link to mechanism that is the most daunting. For instance,

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