This economical arrangement should confer directional sensitivity, which is a minimal requirement of vision[4]. Also, axons connect the photoreceptor cells to the nervous system. This direct evidence for eyes is supported by the fact that the eyespots are located where *Terebratalia*'s orthologues of two homeobox genes (*Pax6* and *Otx*), widely associated with eye development, are co-expressed. In behavioural tests carried out by Passamaneck *et al.*[1] the mature larvae did not respond to light, although it would be surprising if they are indeed blind. The authors report that gastrula embryos, an earlier stage of development at which the animals lack eyes but possess rhodopsin, move towards a light source. How this directionality might be achieved is unclear.

The existence of a ciliary visual photoreceptor in the Lophotrochozoa is not unprecedented. In addition to rhabdomeric eyes, some molluscs, including scallops, have ciliary detectors that initiate shell closure in response to shadows warning of potential predators[2,3]. Such instances of ciliary vision in a predominantly rhabdomeric lineage suggest that natural selection can vary the choice of photoreceptor according to need, and hence that each type has particular advantages.

Ciliary and rhabdomeric phototransduction mechanisms are well studied, and have fundamental differences. For example, the ciliary intracellular signalling pathway uses cyclic nucleotides, whereas the rhabdomeric receptor pathway is based on phospholipase C and calcium ions[2]. But the significance of those differences is not obvious[3]. Insects have rhabdomeric receptors and vertebrates have ciliary receptors, but both have excellent vision. Comparisons of vertebrate and invertebrate eyes usually emphasize physical limitations to light sensing, and imply that the performance of their phototransduction mechanisms is similar; for example, that at low light intensities photoreceptors are near-optimal photon counters.

In this context, the work by Passamaneck *et al.*[1] complements a review by Fain *et al.*[3] of differences in photoreceptor performance. The authors[3] argue that, in bright light, ciliary receptors are superior to rhabdomeric receptors because they consume less energy and suffer less from variation in response time-course — which reduces signal reliability. Also, a higher photopigment density in ciliary receptors enhances their sensitivity. Rhabdomeric receptors, however, function over the huge intensity range from starlight to bright sun, whereas the ciliary mechanism has to trade off response speed against the rate of spontaneous photopigment activation in the absence of light[5]. This spontaneous activation, or dark noise, is equivalent to a constant veiling light, which, in cone photoreceptors, overwhelms vision at low intensities but is insignificant in daylight.

To overcome this problem, vertebrates have a duplex retina of rods and cones. Low spontaneous activity allows rods to signal detection of a single photon, but they suffer from slow responses and take many minutes to recover from an effect known as bleaching, which leaves them blind in daylight. Vertebrate cones have fast responses, but dark noise makes them useless at night. Fain *et al.*[3] suggest that the ancestral chordate had a cone-like ciliary photoreceptor and was active in bright light. The acquisition of separate rods and cones, perhaps following a genome duplication, then allowed early vertebrates to see over as wide a range of light levels as the early protostomes that used the rhabdomeric system for vision.

Taking the work of Passamaneck *et al.*[1] further, one line of study will be to find out whether brachiopod photoreceptors are rod- or cone-like, or indeed have novel properties. Also, little is known about how the planktonic *Terebratalia* larvae live, beyond the facts that they cannot feed and have to find a site to settle. Interestingly, the sessile adults occupy a great range of depths, whereas the larvae's possession of ciliary receptors perhaps implies that they inhabit shallow, sunlit waters. ■

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ATOMIC PHYSICS

A route to quantum magnetism

The trend towards using ultracold atoms as simulators of condensed-matter and many-body phenomena is gaining momentum. These systems can now be used to simulate quantum magnetism. SEE ARTICLE P.307

IAN B. SPIELMAN

At nanokelvin temperatures — 100 billion times closer to absolute zero than room temperature — ultracold atoms are the coldest stuff in the known Universe. At such low temperatures, these quantum gases, each consisting of hundreds to hundreds of millions of atoms, are quintessential quantum many-body systems. Unlike their more conventional solid-state cousins, nearly every property of quantum gases can be controlled[1] in the laboratory with unprecedented flexibility and exquisite precision*.

On page 307 of this issue, Simon *et al.*[2] create one-dimensional chains of ultracold rubidium-87 atoms that behave as if strong magnetic interactions were present[3]. Their novel technique encodes the magnetic properties into the configuration, or geometry, of the atoms in each chain instead of the atoms' quantum mechanical spins as is usually the case in magnetic systems. This increases, by more than a factor of ten, the temperature at which magnetic ordering takes place (when the spatial pattern of spins becomes ordered rather than random), finally allowing quantum magnetism to be studied using ultracold atoms.

Understanding the properties of many-particle interacting systems is a crucial component of modern science. How do interactions between relatively simple components give rise to complex behaviour? How does consciousness emerge from a collection of neurons? How is the large-scale Universe organized? Why do electrons superconduct in some materials and give rise to magnetism in others? Each of these questions involves the emergence of macroscopic properties that are qualitatively distinct from the properties of the individual components.

In physics, we are interested in understanding and classifying the generic ways in which such macroscopic phenomena emerge, linking the microscopic properties of the components (including their environment) to the macroscale. This is usually the domain of condensed-matter physics, in which innumerable interacting electrons in materials give rise to complex phenomena such as superconductivity, the quantum Hall effect and magnetic ordering. Ultracold atoms provide a unique system in which to study many-body physics because the components and their environment are simple and can be nearly perfectly controlled. Indeed, many-body phenomena studied using ultracold atoms have been subjected to unprecedented quantitative comparison with many-body theories. Examples of this

*This article and the paper under discussion[2] were published online on 13 April 2011.

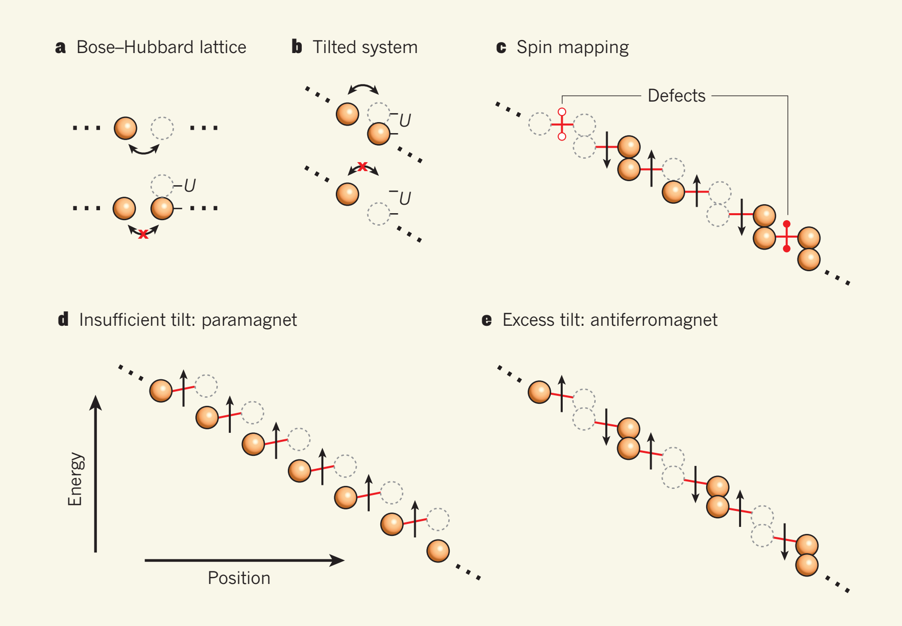

Figure 1 | The principle of Simon and colleagues' effective spin model[2]. **a**, Two examples of a Bose–Hubbard lattice: top, energetically allowed hopping from an occupied atomic site to a neighbouring empty site; bottom, suppression of hopping between neighbouring occupied sites owing to the on-site repulsive energy *U* between two atoms. **b**, Two examples of a tilted lattice. The tilt is sufficient to overcome on-site repulsion, such that the situation in **a** is reversed: top, energetically allowed hopping between neighbouring occupied sites; bottom, suppression of hopping between an occupied site and a neighbouring vacant site. **c**, Mapping of effective spin states (arrows) into different spatial configurations. Defects denote configurations that are not associated with spins, showing that the mapping is approximate. **d**, Insufficient tilt. A system with an average of one atom per site will remain in this configuration, in which the spins align parallel to one another (a paramagnet). **e**, Excess tilt. A system with an average of one atom per site will minimize its energy by creating an alternating array of empty sites and doubly occupied sites, corresponding to an arrangement in which the spins are staggered (an antiferromagnet).

are the phase transition from superfluid to Mott insulator[4], and a continuous transition known as the Bose–Einstein condensate–Bardeen–Cooper–Schrieffer (BEC–BCS) crossover[5,6].

Magnetism is a topic of fundamental importance in condensed-matter physics, having an impact on technology (such as magnetic storage media and some visions of 'spintronic' devices[7,8]) as well as on concepts at the forefront of physics (such as spin liquids[9]). Magnetic systems cannot yet be directly studied using quantum gases because their magnetic-ordering temperatures are tens or hundreds of picokelvins (1 picokelvin is 10^{-12} kelvins). So far, this is too cold even for ultracold atoms.

To bypass this limitation, Simon *et al.*[2] constructed an atomic system in which the spatial configuration of the atoms encodes the 'spin' usually associated with magnetism. They first created a rubidium-87 BEC, in which all the atoms are essentially in the same quantum state, and compressed it into a single two-dimensional (2D) plane. Next, using two independent standing waves of light, they confined the atoms into the sites of a square lattice with one atom per site. One of the two standing waves was made more intense than the other, so that the atoms could 'hop' between sites only in one-dimensional (1D) chains; such hopping is suppressed when neighbouring lattice sites are already occupied, because of the repulsive energy involved in locating two atoms on a single site (Fig. 1a).

To create a magnetic analogue, Simon *et al.*[2] superimposed a magnetic-field gradient on the optical lattice potential, creating an energy difference, or 'tilt', between neighbouring lattice sites. When this energy difference is large enough, it can exceed the repulsive interaction energy, allowing atoms to move from site to site. Thus, a sufficiently large tilt reverses the earlier picture: when a neighbouring site is occupied hopping is allowed (Fig. 1b), but when it is empty hopping is blocked (to conserve energy). When the tilt increases from zero, 1D chains of atoms undergo a transition from one atom per site (Fig. 1d; hopping blocked, analogous to a paramagnet) to a staggered, alternating array of empty sites and doubly occupied sites (Fig. 1e; analogous to an antiferromagnet). Here, the effective magnetism relies on repulsion between atoms, rather than the much smaller exchange interactions between the physical spin states, which normally lead to magnetism in materials. Because every aspect of this system is well understood, the authors were able to directly compare their results with the 1D quantum Ising magnetic model they sought to realize — and found spectacular agreement.

Like the Brownian motion of pollen grains suspended in water, physical systems are usually coupled to a source of random thermal motion: an environment. The successful implementation of this technique relies heavily on a second feature of ultracold atom systems: they are not well connected to such an environment. When the magnetic-field gradient tilts the lattice potential, essentially creating a hill for the atoms, one might expect the atoms to reduce their energy by all moving down the hill. Because the atoms are not linked to an environment, there is no mechanism for them to begin this downhill motion and nowhere for the excess energy to go, so instead the system remains within the subset of spatial configurations that are analogous to spins.

Simon and colleagues[2] demonstrate a powerful experimental technique for creating analogues to spin systems. However, the 1D quantum Ising model is well understood from modern theoretical techniques[10], and the small systems studied here can be numerically exactly solved by brute force. It is the next step that is profound: creating spin systems that are currently insoluble by known analytical or numerical techniques. For example, the extensions of this work discussed by Sachdev *et al.*[3] would allow the simulation of 2D 'frustrated' spin systems, for some of which an exotic, ground (minimal-energy) state of matter known as a quantum spin liquid is expected[9]. As the complexity and control of ultracold atoms have continued to increase, it has become evident that they are not simply emulators of condensed-matter systems, but fascinating quantum many-body systems in their own right. As such, they may well exhibit behaviours that do not exist in any other physical system. Extensions of Simon and colleagues' technique[2] should allow the construction of nearly arbitrary spin systems, which will be a crucial leap in that direction. ■

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