ATOMIC AND MOLECULAR PHYSICS

Polar molecules in topological order

Quantum states of matter with topological order are of great fundamental — and potential practical — interest. Polar molecules stored in optical lattices could offer a platform for realizing such ‘exotic’ states.

MACIEJ LEWENSTEIN
is at the Institució Catalana de Recerca i Estudis Avançats (ICREA) and the Institut de Ciències Fotòniques (ICFO), 08860 Castelldefels (Barcelona), Spain.
e-mail: maciej.lewenstein@icfo.es

Ultracold atomic and molecular gases in optical lattices allow for experimental studies of strongly correlated quantum states of matter. When appropriately designed, they may serve as nearly perfect realizations of spin models, arrangements that are simple in structure, but complex in behaviour. Such models have been intensively studied by condensed-matter physicists over the last 30 years. Often they show quantum phase transitions that do not fit into the standard Landau theory of phase transitions, leading to previously unknown ‘exotic’ quantum states of matter. So far, most of the proposals to realize such models with ultracold atoms or molecules have been extremely demanding experimentally, and rather restricted with regard to controlling the effective couplings between the constituent spins. In this issue, Micheli, Brennen and Zoller[1] kill two birds with one stone: they propose to combine microwave excitations with dipole–dipole interactions and spin–rotation couplings in polar molecules, to realize effective spin models with both the desired form of two-spin interactions and coupling strengths that allow them to reach the so-called ‘low-temperature limit’ at experimentally accessible temperatures.

The Landau theory of second-order phase transitions associates with every transition a symmetry-breaking mechanism, and with every ordered phase an appearance of a local order parameter. This is particularly true for quantum phase transitions that occur at ultralow temperatures and are driven by quantum fluctuations. In recent decades, condensed-matter theorists have been fascinated by quantum phase transition and ‘exotic’ quantum phases that do not follow this standard pattern. Such exotic phases happen to occur in some highly idealized spin models in two dimensions, but so far have hardly been observed in solid-state experiments.

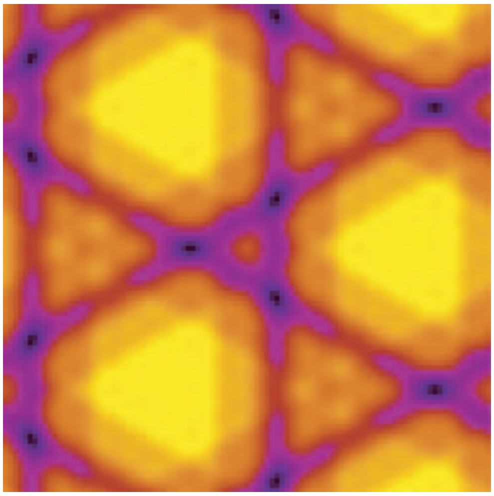
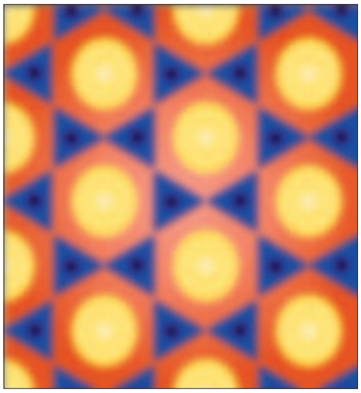


Figure 1 Atoms and molecules can be placed in a desired arrangement by creating optical lattices with the required geometry. Depicted here is a trimerized Kagomé lattice[10]. Colours indicate the strength of the optical potential: minima are shown in black.

In a recent review, Fisher[2] introduced two classes of exotic phase: topological and critical spin liquids. A topologically ordered spin liquid behaves peculiarly as the topology of the system changes. The ground state in such a system is degenerate, and the degeneracy depends on the topology of the surface on which the states live. To illustrate such behaviour, it helps to associate the appearance of spin liquids with frustration in antiferromagnetic systems, a view that Lhuillier and her collaborators introduced[3]. The simplest example is the Heisenberg antiferromagnet in a triangular lattice, where neighbouring spins cannot attain the standard antiferromagnetic Néel order (that is, an alternating sequence of up and down spins). A more complex example is given by a Heisenberg antiferromagnet in the so-called trimerized Kagomé lattice[10] (Fig. 1). The spins organize themselves in nearest-neighbour pairs, where they form singlets or valence bonds. There are numerous coverings of the Kagomé lattice by valence bonds, and the true ground state and low-energy excitations are built as superpositions of various coverings. The resulting state is the famed ‘resonating-valence-bond state’, introduced by Anderson[2].

Spin models that have topological order are interesting for applications, in particular



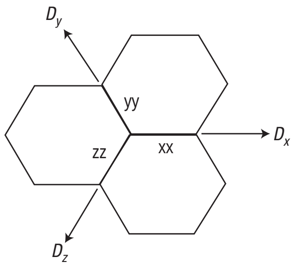


Figure 2 Towards phases with topological order. a The optical honeycomb lattice[9] allows the realization of a topologically protected quantum memory[5]. b In this model, couplings between spins depend on the direction of the bonds between them. Reprinted with permission from ref. 9. Copyright 2003 American Physical Society.

in the realm of quantum information, because they are resilient to arbitrary perturbations of the underlying hamiltonian. Duoçot *et al.*[4], for example, have proposed a model in a square lattice, in which nearest-neighbour spins couple via their *x*- or *z*-components, depending on the direction of the bond. Such systems admit two-fold-degenerate ground states that are extremely insensitive to noise, and can thus serve as a 'protected' qubit. Kitaev[5] went further and proposed a model built on a honeycomb lattice (Fig. 2a), in which the spins' *x*-, *y*- and *z*-components couple, again depending on the bond direction (Fig. 2b). This model is particularly intriguing because — in certain limits — it allows the realization of a topologically protected quantum memory.

Theorists realized very early on that ultracold atomic or molecular gases in optical lattices offer a unique platform for realizing and controlling strongly correlated quantum states[6]. Experiments, ranging from the seminal observation of a superfluid–Mott-insulator transition[7] to the most recent observation of the Bose glass[8], clearly demonstrate the strength of the approach. In the strong-coupling limit, ultracold lattice gases are often described by spin models. Clearly, in the limit, we could also try to realize exotic spin-liquid phases, or phases with topological order. Spin (or pseudospin) states of particles in such systems would correspond to certain internal or motional states. Duan, Demler and Lukin[9] proposed to use atoms with two internal states in an optically formed honeycomb lattice (Fig. 2a), and to harness laser-assisted tunnelling in such lattices to realize the Kitaev model[5]. In another proposal, Damski *et al.*[10] suggest using superlattice techniques — additions of several optical lattices — to create a trimerized Kagomé lattice (Fig. 1). Unfortunately, the experimental realizations of both proposals, although not excluded, remain difficult, because in the strong coupling limit, the energy associated with hoping of particles, t, is much smaller than the interaction energy, U, and the characteristic energy scales are of order t^2/U, corresponding to (extremely low) temperatures of around 10 nanokelvins.

The proposal of Micheli *et al.*[1] overcomes these difficulties: by using the gas of ultracold heteronuclear polar molecules in the lattice, and by using appropriately designed microwave excitation to the first excited rotation states, they achieve a universal 'toolbox' for effective spin models, with designable range and spatial anisotropy of dipole–dipole couplings. And, importantly, the strength of these couplings is quite sizeable, owing to the large dipole moment of heteronuclear molecules, allowing operation in a regime of higher temperatures. The precondition for realization of this proposal, though, is the creation of an ultracold gas of heteronuclear molecules. This has not been achieved so far. Experimental progress in this direction in recent years, however, has been so rapid[11] that it seems safe to assume that in a few years the proposal by Micheli *et al.* will be realized, and polar molecules in topological order will no longer be just a dream.

REFERENCES

[Note: page references XXX to be resolved]

1. Micheli, A., Brennen, G. K. & Zoller, P. *Nature Phys.* **2**, XXX–XXX (2006).
2. Alet, F., Walczak, A. M. & Fisher, M. P. A. Preprint at <http://arxiv.org/abs/cond-mat/0511516> (2005).
3. Misguich, G. & Lhuillier, C. in *Frustrated Spin Systems* (ed. Diep, H. T.) 229–306 (World Scientific, Singapore, 2005).
4. Duoçot, B., Feigel'man, M. V., Ioffe, L. B. & Ioselevich, A. S. *Phys. Rev. B* **71**, 024505 (2005).

[Author: Should references 5 and 6 be Ann. Phys. (Leipz.) or Ann. Phys. (NY)?]

5. Kitaev, A. Yu. *Ann. Phys.* **321**, 2–111 (2006).
6. Jaksch, D. & Zoller, P. *Ann. Phys.* **315**, 52–79 (2005).
7. Greiner, M., Mandel, O., Esslinger, T., Hänsch, T. W. & Bloch, I. *Nature* **415**, 39–44 (2002).
8. Fallani, L., Lye, J. E., Guarrera, V., Fort, C. & Inguscio, M. Preprint at <http://arxiv.org/abs/cond-mat/0603655> (2006).
9. Duan, L. M., Demler, E. & Lukin, M. D. *Phys. Rev. Lett.* **91**, 090402 (2003).
10. Damski, B. *et al. Phys. Rev. A* **72**, 053612 (2005).

[Please check form of reference for no. 11.]

11. *Special Issue on Ultracold Polar Molecules: Formation and Collisions*, *Eur. Phys. J.* **D31** (2004).