Science AAAS

Cold-Atom Magnetism

J. V. Porto

Science **340**, 1297 (2013);
DOI: 10.1126/science.1239873

invite further investigation of *Ir76b*, which is also expressed in a variety of cells that have not been previously implicated in salt taste.

References

1. G. S. Suh *et al.*, *Nature* **431**, 854 (2004).
2. C. Faucher *et al.*, *J. Exp. Biol.* **209**, 2739 (2006).
3. H.-H. Lin *et al.*, *Science* **340**, 1338 (2013).
4. Y. V. Zhang, J. Ni, C. Montell, *Science* **340**, 1334 (2013).
5. M. de Bruyne, K. Foster, J. R. Carlson, *Neuron* **30**, 537 (2001).
6. G. S. Suh *et al.*, *Curr. Biol.* **17**, 905 (2007).
7. S. L. Turner, A. Ray, *Nature* **461**, 277 (2009).
8. C. Y. Su, K. Menuz, J. Reisert, J. R. Carlson, *Nature* **492**, 66 (2012).
9. C. M. Root *et al.*, *Neuron* **59**, 311 (2008).
10. S. R. Olsen, R. I. Wilson, *Nature* **452**, 956 (2008).
11. H. Ishimoto, T. Tanimura, *Cell. Mol. Life Sci.* **61**, 10 (2004).
12. J. Chandrashekar *et al.*, *Nature* **464**, 297 (2010).
13. Y. Oka *et al.*, *Nature* **494**, 472 (2013).

10.1126/science.1240139

PHYSICS

Cold-Atom Magnetism

A trapped cloud of cold atoms can be used to simulate magnetism found in condensed matter systems.

J. V. Porto

How do you cool something that is already the coldest stuff in the universe? That is the challenge facing physicists who are trying to use extremely dilute ultracold atomic gases to model condensed matter systems. Cold gases hold promise for simulating a variety of many-body problems, but progress has been limited by the inability to reach sufficiently low temperatures. On page 1307 of this issue, Greif *et al.* (*1*) show that by dynamically manipulating the atom-trapping potential, a gas of ultracold potassium atoms could be cooled enough to observe magnetic correlations that arise only at sufficiently low temperatures. These results mark an important step toward realizing quantum magnetism with cold atoms, an achievement that could lead to a better understanding of a range of interesting states of matter.

Since the observation that ultracold atoms in optical lattices represent a nearly perfect realization of the iconic Bose-Hubbard model of interacting particles in a lattice (*2*), there has been rapid growth in the study of many-body physics with cold, trapped atoms. At first glance, it may seem unlikely that a weakly interacting "material" that is 10,000 times less dense than air could resemble a condensed matter material at all. Although cold-atom densities and energy scales are certainly much smaller than in real solids, this is often merely a difference in scale. In many cases, the physics is essentially the same, requiring only that the gas be brought to an appropriately low temperature where the correlated physics of interest occurs. Because atomic gases can be cooled to low temperatures, they provide an attractive avenue for studying "condensed matter" physics in a controlled, nearly defect-free environment.

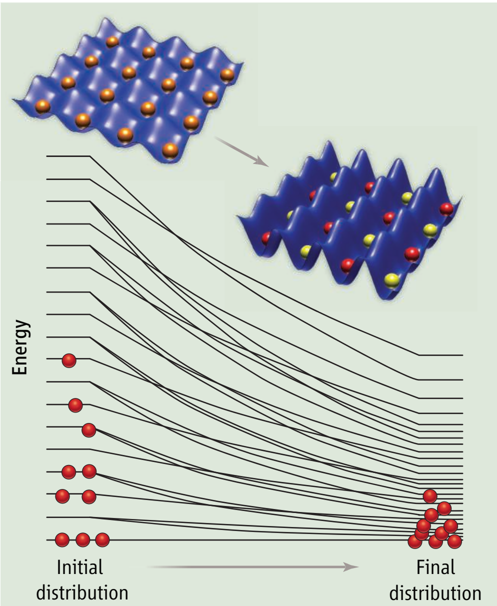
Joint Quantum Institute, National Institute of Standards and Technology, 100 Bureau Drive, Stop 8424, Gaithersburg, MD 20899–8424, USA. E-mail: trey@nist.gov

Starting with the realization of a Mott-insulating state (*3*), this approach has been successfully applied to a variety of problems (*4*).

Unfortunately, many of the more interesting problems in condensed matter physics, particularly involving exotic states arising from quantum magnetism, require temperatures even lower than those achievable with current techniques. Based on exchange interactions between atoms in neighboring sites (*5*), the energy scales for many proposed cold-atom realizations of magnetism are much smaller than the typical onsite interaction energies. Despite the direct analogy with condensed matter systems, this cooling problem is complicated by a practical difference with real solids: It is very difficult to have an independent refrigerant in contact with a cold, dilute gas. New techniques for cooling are therefore needed (*6*).

One proposed solution is to use a separate cold-atom gas as a refrigerant (*7*), but this can be difficult to implement. Another approach is to dynamically manipulate the energy spectrum of the isolated system to reduce its temperature (*8*, *9*). This approach has a direct analogy with adiabatic spin demagnetization cooling, where decreasing the internal energy scale of thermally isolated spins lowers the overall energy scale and leads to cooling. The key observation is that, whereas the second law of thermodynamics states that isolated systems cannot lower their entropy, there is no such restriction on the temperature if the internal energy spectrum of the system is changed. Such spin-demagnetization has been used to cool atoms in optical lattices (*10*), and entropy redistribution effects occur in large spin systems (*11*) and in nearly defect-free cold-atom crystals (*12*, *13*).

Greif *et al.* use a similar approach in two-dimensional (2D) systems with magnetic interactions (*5*). Using a dynamically controlled multiperiod lattice, they raise the lattice potential along a subset of the lattice bonds. This changes the overall density of states of the system, thereby lowering the temperature. By raising the lattice along bonds that tend to isolate pairs of dimerized sites, they observe thermally equilibrated magnetic correlations within the dimerized sites. The resulting state is similar to spin-correlated states constructed by direct spin



Adiabatic cooling. Atoms are initially cooled as far as possible with conventional methods in a 2D isotropic lattice. Black lines indicate schematically the density of states, and the initial thermal distribution is indicated with red dots on the left. Raising the lattice depth along one direction isolates individual 1D systems and compresses the density of states, particularly for degrees of freedom associated with the now deep-lattice direction. The resulting thermal distribution is compressed (cooled) with respect to the degrees of freedom along the 1D tubes, giving rise to the observed magnetic correlations.

manipulation (*14*), except that here the correlations arise thermodynamically.

In the second groundbreaking experiment, they demonstrate correlations in extended 1D systems. By raising the lattice along one direction, they convert the 2D lattice into an array of 1D systems (see the figure). The isolated 1D systems are sufficiently cooled to demonstrate antiferromagnetic spin correlations between neighboring spins. Remarkably, the correlations are observed to be symmetric, independent of which of a given spin's two neighbors are measured. This indicates that the adiabatically generated correlations extend beyond just two sites, a major achievement for cold-atom realization of magnetism.

The work here opens the door for a new set of challenges. Such low temperatures require careful understanding and control of all heating rates. This in itself can be an interesting area of research, because the mechanisms for heating can depend in detail on the many-body states (*15*). Also, because the adiabatic approach requires subsystems in which to dump entropy, it is not clear how far the technique can be pushed, or the best way to create cooling in other 2D lattice geometries. Nonetheless, the demonstration by Greif *et al.* of magnetic correlations in an extended cold-atom system provides optimism that these challenges can be overcome.

References

1. D. Greif *et al.*, *Science* **340**, 1307 (2013).
2. D. Jaksch *et al.*, *Phys. Rev. Lett.* **81**, 3108 (1998).
3. M. Greiner *et al.*, *Nature* **415**, 39 (2002).
4. I. Bloch *et al.*, *Rev. Mod. Phys.* **80**, 885 (2008).
5. L. M. Duan *et al.*, *Phys. Rev. Lett.* **91**, 090402 (2003).
6. D. C. McKay, B. DeMarco, *Rep. Prog. Phys.* **74**, 054401 (2011).
7. A. Griessner *et al.*, *Phys. Rev. Lett.* **97**, 220403 (2006).
8. J. -S. Bernier *et al.*, *Phys. Rev. A* **79**, 061601 (2009).
9. T. L. Ho, Q. Zhou, *Proc. Natl. Acad. Sci. U.S.A.* **106**, 6916 (2009).
10. P. Medley *et al.*, *Phys. Rev. Lett.* **106**, 195301 (2011).
11. S. Taie *et al.*, *Nat. Phys.* **8**, 825 (2012).
12. W. S. Bakr *et al.*, *Science* **329**, 547 (2010).
13. J. F. Sherson *et al.*, *Nature* **467**, 68 (2010).
14. S. Trotzky *et al.*, *Science* **319**, 295 (2008).
15. H. Pichler *et al.*, *Phys. Rev. A* **82**, 063605 (2010).

10.1126/science.1239873

PHYSICS

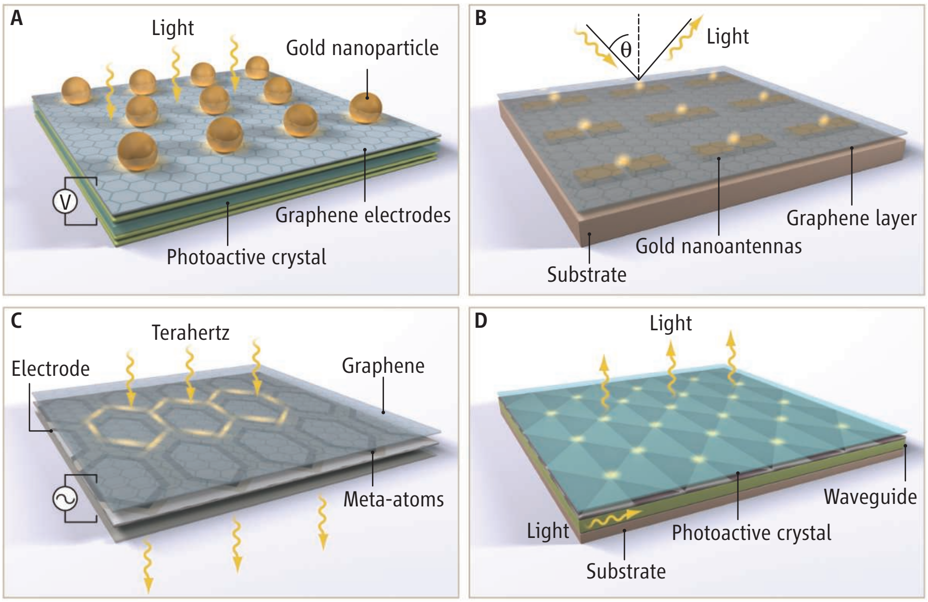
Two Two-Dimensional Materials Are Better than One

Combining 2D materials and 2D metasurfaces enables the fabrication of photonic devices based on extreme interactions between electrons and light.

Joachim M. Hamm and Ortwin Hess

Extraordinary electronic or optical properties can result when layered solids are realized as two-dimensional (2D) materials (single or few-layer sheets), as is the case when graphene is formed from graphite. Optical properties can also be enhanced by restructuring materials at subwavelength scales into metamaterials, such as enhancing the plasmonic properties of gold—the coupling of light to electrons—by forming nanoparticles. Combining these approaches can lead to devices with capabilities that are otherwise difficult to realize. For example, for photovoltaic devices or sensors, materials with high electronic conductivity could be optically thick (to efficiently absorb light) but dimensionally thin (to impart flexibility and light weight). On page 1311 of this issue, Britnell *et al.* (*1*) combined highly conductive graphene and optically active 2D transition metal dichalcogenides into a heterostructure that photoexcites electron-hole pairs within a band-gap material. These carriers were separated with a p-n junction and extracted as a photocurrent with transparent graphene electrodes (graphene), and the performance was enhanced with plasmonic gold nanoparticles.

How does the light-matter interaction become stronger by making a particular material to become 2D, e.g., by exfoliation of single layers and making it so thin that it effectively has no thickness relative to the wavelength of light? This surprising property is directly related to the presence of critical points that generate in 2D or 1D (but not in 3D) the so-called Van Hove singularities in the electronic structure. Britnell *et al.* report that for the photoactive transition metal dichalcogenides such as molybdenum



Uniting flat materials. Various ultraflat photonic devices that could be built through the combination of 2D electronic materials and 2D photonic metasurfaces are illustrated. (**A**) Ultrathin broadband photovoltaic devices could be realized by combining 2D materials and broadband light harvesting (*1*). (**B**) Label-free single-molecule detectors could be achieved by exploiting a diffractive coupling between plasmonic nanoantennas functionalized by a graphene layer (*10*). (**C**) A polarization-independent terahertz modulator could be made by using gate-tunable graphene embedded in a metamaterial structure (*11*). (**D**) Ultrafast and broadband metasurface emitters could be made by tailoring the 2D active material to operate in visible light or in the terahertz regime (*8*, *12*).

The Blackett Laboratory, Department of Physics, Imperial College London, London SW7 2AZ, UK. E-mail: j.hamm@imperial.ac.uk; o.hess@imperial.ac.uk