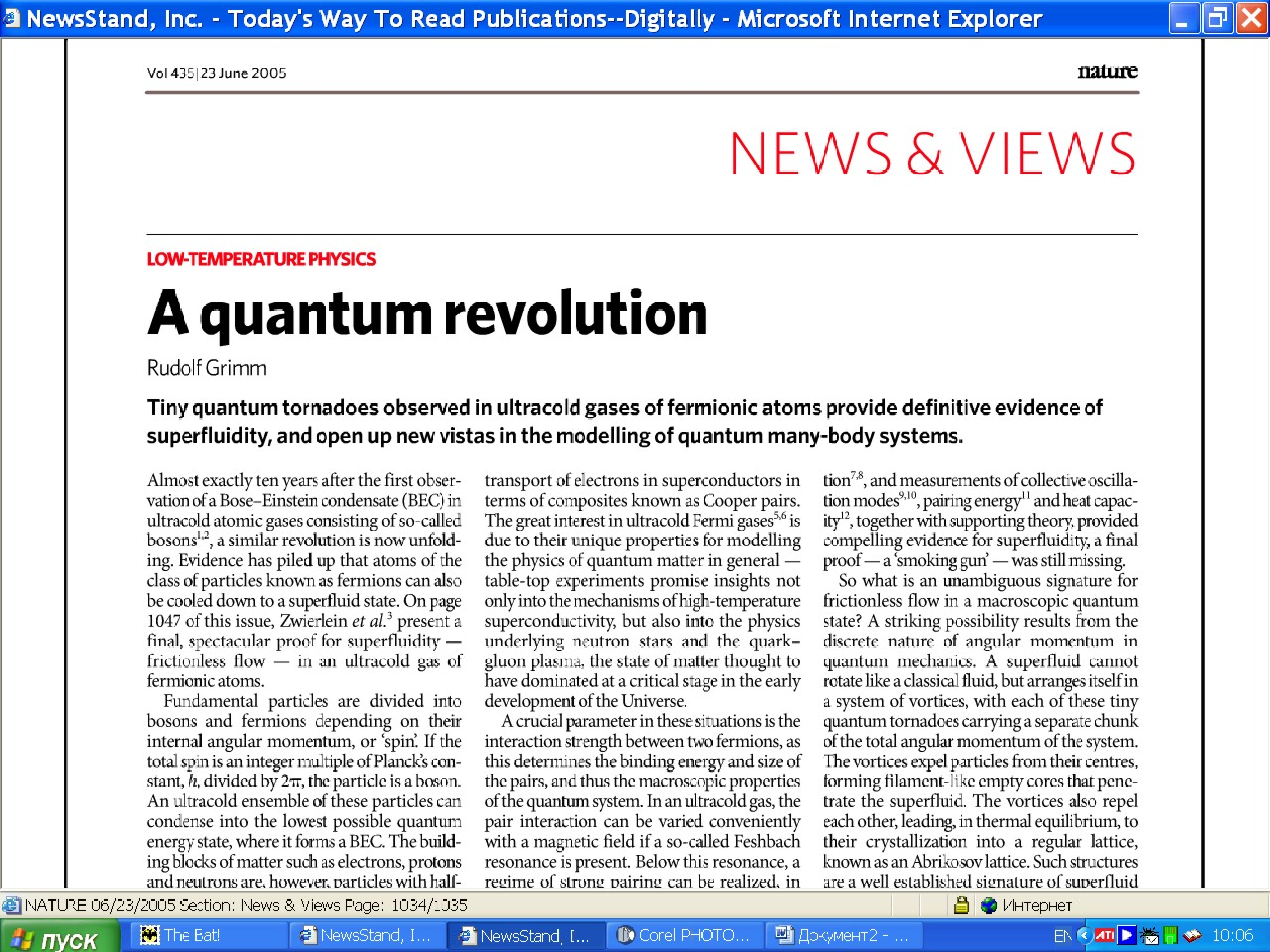


NEWS & VIEWS

LOW-TEMPERATURE PHYSICS

A quantum revolution

Rudolf Grimm

Tiny quantum tornadoes observed in ultracold gases of fermionic atoms provide definitive evidence of superfluidity, and open up new vistas in the modelling of quantum many-body systems.

Almost exactly ten years after the first observation of a Bose–Einstein condensate (BEC) in ultracold atomic gases consisting of so-called bosons[1,2], a similar revolution is now unfolding. Evidence has piled up that atoms of the class of particles known as fermions can also be cooled down to a superfluid state. On page 1047 of this issue, Zwierlein *et al.*[3] present a final, spectacular proof for superfluidity — frictionless flow — in an ultracold gas of fermionic atoms.

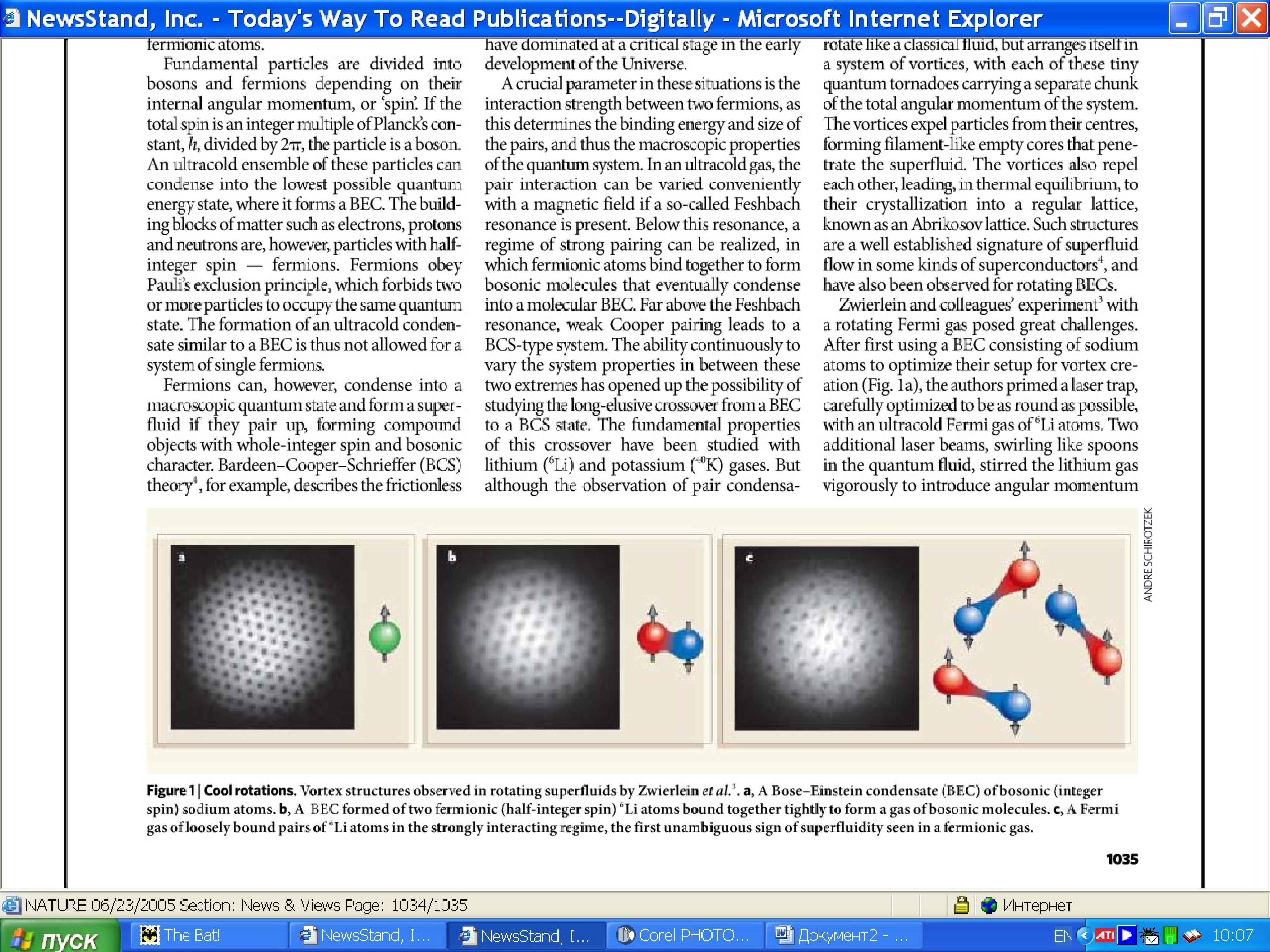
Fundamental particles are divided into bosons and fermions depending on their internal angular momentum, or 'spin'. If the total spin is an integer multiple of Planck's constant, h, divided by 2π, the particle is a boson. An ultracold ensemble of these particles can condense into the lowest possible quantum energy state, where it forms a BEC. The building blocks of matter such as electrons, protons and neutrons are, however, particles with half-

transport of electrons in superconductors in terms of composites known as Cooper pairs. The great interest in ultracold Fermi gases[5,6] is due to their unique properties for modelling the physics of quantum matter in general — table-top experiments promise insights not only into the mechanisms of high-temperature superconductivity, but also into the physics underlying neutron stars and the quark–gluon plasma, the state of matter thought to have dominated at a critical stage in the early development of the Universe.

A crucial parameter in these situations is the interaction strength between two fermions, as this determines the binding energy and size of the pairs, and thus the macroscopic properties of the quantum system. In an ultracold gas, the pair interaction can be varied conveniently with a magnetic field if a so-called Feshbach resonance is present. Below this resonance, a regime of strong pairing can be realized, in

tion[7,8], and measurements of collective oscillation modes[9,10], pairing energy[11] and heat capacity[12], together with supporting theory, provided compelling evidence for superfluidity, a final proof — a 'smoking gun' — was still missing.

So what is an unambiguous signature for frictionless flow in a macroscopic quantum state? A striking possibility results from the discrete nature of angular momentum in quantum mechanics. A superfluid cannot rotate like a classical fluid, but arranges itself in a system of vortices, with each of these tiny quantum tornadoes carrying a separate chunk of the total angular momentum of the system. The vortices expel particles from their centres, forming filament-like empty cores that penetrate the superfluid. The vortices also repel each other, leading, in thermal equilibrium, to their crystallization into a regular lattice, known as an Abrikosov lattice. Such structures are a well established signature of superfluid



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Fermions can, however, condense into a macroscopic quantum state and form a superfluid if they pair up, forming compound objects with whole-integer spin and bosonic character. Bardeen–Cooper–Schrieffer (BCS) theory[4], for example, describes the frictionless have dominated at a critical stage in the early development of the Universe.

A crucial parameter in these situations is the interaction strength between two fermions, as this determines the binding energy and size of the pairs, and thus the macroscopic properties of the quantum system. In an ultracold gas, the pair interaction can be varied conveniently with a magnetic field if a so-called Feshbach resonance is present. Below this resonance, a regime of strong pairing can be realized, in which fermionic atoms bind together to form bosonic molecules that eventually condense into a molecular BEC. Far above the Feshbach resonance, weak Cooper pairing leads to a BCS-type system. The ability continuously to vary the system properties in between these two extremes has opened up the possibility of studying the long-elusive crossover from a BEC to a BCS state. The fundamental properties of this crossover have been studied with lithium (^{6}Li) and potassium (^{40}K) gases. But although the observation of pair condensa- rotate like a classical fluid, but arranges itself in a system of vortices, with each of these tiny quantum tornadoes carrying a separate chunk of the total angular momentum of the system. The vortices expel particles from their centres, forming filament-like empty cores that penetrate the superfluid. The vortices also repel each other, leading, in thermal equilibrium, to their crystallization into a regular lattice, known as an Abrikosov lattice. Such structures are a well established signature of superfluid flow in some kinds of superconductors[4], and have also been observed for rotating BECs.

Zwierlein and colleagues' experiment[3] with a rotating Fermi gas posed great challenges. After first using a BEC consisting of sodium atoms to optimize their setup for vortex creation (Fig. 1a), the authors primed a laser trap, carefully optimized to be as round as possible, with an ultracold Fermi gas of ^{6}Li atoms. Two additional laser beams, swirling like spoons in the quantum fluid, stirred the lithium gas vigorously to introduce angular momentum

Figure 1 | Cool rotations. Vortex structures observed in rotating superfluids by Zwierlein *et al.*[3]. **a**, A Bose–Einstein condensate (BEC) of bosonic (integer spin) sodium atoms. **b**, A BEC formed of two fermionic (half-integer spin) ^{6}Li atoms bound together tightly to form a gas of bosonic molecules. **c**, A Fermi gas of loosely bound pairs of ^{6}Li atoms in the strongly interacting regime, the first unambiguous sign of superfluidity seen in a fermionic gas.

to the system, which was then given a variable time for formation and crystallization of the vortices.

The vortex cores are far too small to be resolved by optical imaging. So Zwierlein and colleagues magnified the vortex cores and the whole vortex lattice by turning off the laser trap and releasing the system into free space, where it expanded. They also increased the size of the vortex cores, and thus their visibility, by changing the interaction strength during the expansion.

The authors first demonstrated the formation of vortex lattices in the lithium gas in the molecular BEC regime. Here the size of the fermion pairs is small compared with the typical interparticle distances, and a closely bound, bosonic molecule is formed (Fig. 1b). In the strongly interacting regime close to the Feshbach resonance on the BCS side, the pair size is comparable to typical interparticle distances. Here, the fermion pairs cannot bind together to form isolated molecules — yet similar vortex patterns were observed (Fig. 1c). The time required for the formation of the vortex lattice was about a hundred times longer than the expansion timescale — ruling out the possibility that vortices are formed during expansion.

The spectacular observation of vortices in a Fermi gas heralds the advent of a new era of research reaching far beyond Bose–Einstein condensation. As an immediate experimental step, interfering light fields can be used to simulate a crystal lattice[13], providing a unique tool for solving problems in condensed-matter physics[14]. And the amazing level of control demonstrated in the work of Zwierlein *et al.*[3]

NEUROSCIENCE

Friends and grandmothers

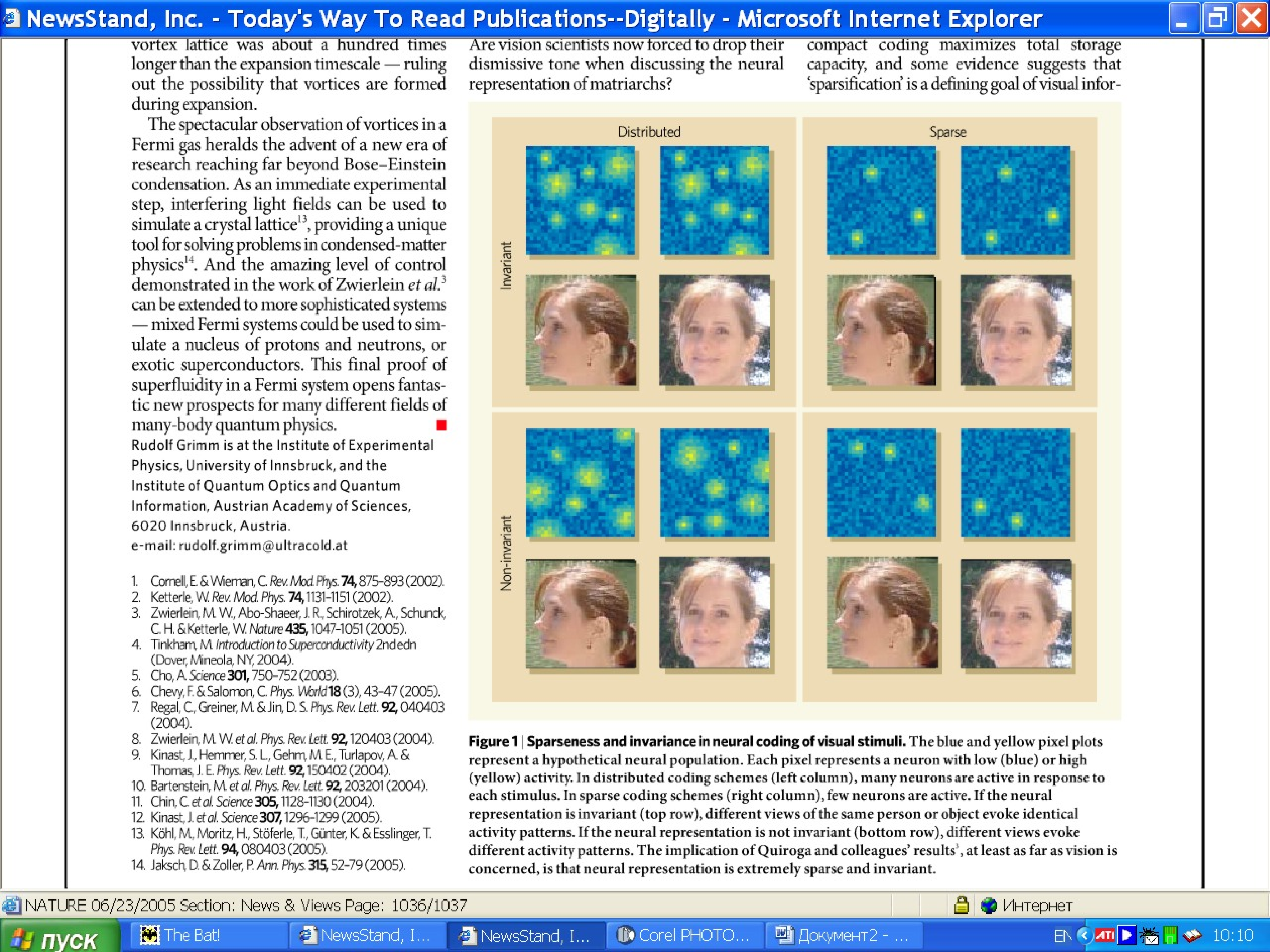
Charles E. Connor

How do neurons in the brain represent movie stars, famous buildings and other familiar objects? Rare recordings from single neurons in the human brain provide a fresh perspective on the question.

'Grandmother cell' is a term coined by J. Y. Lettvin to parody the simplistic notion that the brain has a separate neuron to detect and represent every object (including one's grandmother)[1]. The phrase has become a shorthand for invoking all of the overwhelming practical arguments against a one-to-one object coding scheme[2]. No one wants to be accused of believing in grandmother cells. But on page 1102 of this issue, Quiroga *et al.*[3] describe a neuron in the human brain that looks for all the world like a 'Jennifer Aniston' cell. Ms Aniston could well become a grandmother herself someday. Are vision scientists now forced to drop their dismissive tone when discussing the neural representation of matriarchs?

A more technical term for the grandmother issue is 'sparseness' (Fig. 1). At earlier stages in the brain's object-representation pathway, the neural code for an object is a broad activity pattern distributed across a population of neurons, each responsive to some discrete visual feature[4]. At later processing stages, neurons become increasingly selective for combinations of features[5], and the code becomes increasingly sparse — that is, fewer neurons are activated by a given stimulus, although the code is still population-based[6]. Sparseness has its advantages, especially for memory, because compact coding maximizes total storage capacity, and some evidence suggests that 'sparsification' is a defining goal of visual infor-

NATURE 06/23/2005 Section: News & Views Page: 1036/1037



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The spectacular observation of vortices in a Fermi gas heralds the advent of a new era of research reaching far beyond Bose–Einstein condensation. As an immediate experimental step, interfering light fields can be used to simulate a crystal lattice[13], providing a unique tool for solving problems in condensed-matter physics[14]. And the amazing level of control demonstrated in the work of Zwierlein *et al.*[3] can be extended to more sophisticated systems — mixed Fermi systems could be used to simulate a nucleus of protons and neutrons, or exotic superconductors. This final proof of superfluidity in a Fermi system opens fantastic new prospects for many different fields of many-body quantum physics. ■

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1. Cornell, E. & Wieman, C. *Rev. Mod. Phys.* **74,** 875–893 (2002).
2. Ketterle, W. *Rev. Mod. Phys.* **74,** 1131–1151 (2002).
3. Zwierlein, M. W., Abo-Shaeer, J. R., Schirotzek, A., Schunck, C. H. & Ketterle, W. *Nature* **435,** 1047–1051 (2005).
4. Tinkham, M. *Introduction to Superconductivity* 2nd edn (Dover, Mineola, NY, 2004).
5. Cho, A. *Science* **301,** 750–752 (2003).
6. Chevy, F. & Salomon, C. *Phys. World* **18** (3), 43–47 (2005).
7. Regal, C., Greiner, M. & Jin, D. S. *Phys. Rev. Lett.* **92,** 040403 (2004).
8. Zwierlein, M. W. *et al. Phys. Rev. Lett.* **92,** 120403 (2004).
9. Kinast, J., Hemmer, S. L., Gehm, M. E., Turlapov, A. & Thomas, J. E. *Phys. Rev. Lett.* **92,** 150402 (2004).
10. Bartenstein, M. *et al. Phys. Rev. Lett.* **92,** 203201 (2004).
11. Chin, C. *et al. Science* **305,** 1128–1130 (2004).
12. Kinast, J. *et al. Science* **307,** 1296–1299 (2005).
13. Köhl, M., Moritz, H., Stöferle, T., Günter, K. & Esslinger, T. *Phys. Rev. Lett.* **94,** 080403 (2005).
14. Jaksch, D. & Zoller, P. *Ann. Phys.* **315,** 52–79 (2005).

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Figure 1 | Sparseness and invariance in neural coding of visual stimuli. The blue and yellow pixel plots represent a hypothetical neural population. Each pixel represents a neuron with low (blue) or high (yellow) activity. In distributed coding schemes (left column), many neurons are active in response to each stimulus. In sparse coding schemes (right column), few neurons are active. If the neural representation is invariant (top row), different views of the same person or object evoke identical activity patterns. If the neural representation is not invariant (bottom row), different views evoke different activity patterns. The implication of Quiroga and colleagues' results[3], at least as far as vision is concerned, is that neural representation is extremely sparse and invariant.