

colleagues' finely tuned H_2CO densitometer[1] to Hathi and colleagues' high-redshift galaxy sample[2]. But even that capability might come with the Square Kilometre Array[18], an international radio telescope currently at the planning stage. ■

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NANOELECTRONICS

Spin surprise in carbon

Arne Brataas

Spintronics is an emerging branch of electronics that exploits electrons' spin, rather than charge. In carbon nanotubes, the coupling of this spin with electron motion could offer a desirable way to control quantum information.

Electrons have an electrical charge and a spin — an intrinsic angular momentum as if the electron were spinning around its own axis. The spin adopts one of two states, the manipulation and detection of which forms the basis of a branch of electronics known as spintronics. If the spin interacts with electron motion, it can cause the spin to change state, leading to loss of information in a spintronics device. In carbon, these spin–orbit interactions were thought to be weak, making the material ideal for sending spin information over long distances. In this issue, McEuen and colleagues[1] (page 448) show that in carbon nanotubes, spin and orbital motion are more strongly coupled than previously thought. Far from being a bad thing, this opens up new possibilities for manipulating electron spin.

The spin state of electrons can be used as a binary variable in much the same way that oppositely charged particles (electrons and positively charged 'holes') are used in semiconductor devices. This has opened up new fields of science and technology and has already led to commercial devices, such as read heads for computer hard disks. These devices rely on a spin-dependent principle known as giant magnetoresistance, the discovery of which won the 2007 Nobel Prize in Physics for Albert Fert and Peter Grünberg[2].

Carbon nanotubes have great appeal as possible components of spintronics devices. These carbon structures consist of sheets of carbon atoms rolled up into a cylinder, and this topology separates electron movement into two orbitals of equal energy: one that circles the tube in a clockwise direction, and one that circles anticlockwise. This simple orbital arrangement could make it easier to manipulate electrons and offers another binary variable that might be useful for carrying information. Furthermore, spintronic signals in carbon are expected to be stable because the small size of the nucleus reduces electronic spin–orbit interactions, and because carbon nuclei have no nuclear spin to cause the signal to decay.

McEuen and colleagues[1] now demonstrate that in carbon nanotubes the interaction between an electron's spin and its orbital motion is strong. This is no mean feat, because the effects of the spin–orbit interaction first have to be isolated from those of other interactions. In particular, electron–electron interactions in carbon nanotubes have a marked effect on electron properties. The authors addressed this problem by constructing a nanotube quantum dot — a nanotube that contains just one, or a few, charge carriers (electrons or holes) constrained in all three spatial dimensions.

The authors used a method known as a Coulomb blockade to confine the charge carriers. This involves applying a 'gate' voltage part of the way along the nanotube, inducing a background potential that dictates the number of electrons or holes in the dot. They also applied a 'source-drain' voltage across contacts placed at either end of the nanotube. By measuring the current through the nanotube, the authors were able to determine a quantity known as differential conductance (a measure of the rate of change of current as a function of the source-drain voltage). When they plotted the differential conductance against the gate and source-drain voltage, they observed peaks that correspond to the energy required to add or subtract a confined electron (or hole). This allowed them to calculate the corresponding energy levels for these charge carriers.

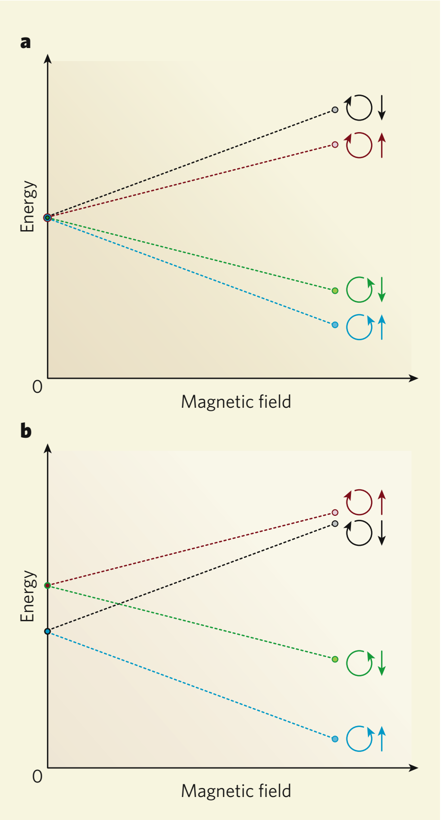

Figure 1 | Spin–orbit coupling of electrons in carbon nanotubes. Electrons in carbon nanotubes exist in quantized energy levels. **a**, The ground state was believed to consist of four states of equal energy, representing different combinations of orbital states (clockwise and anticlockwise motion, indicated by circular arrows) and spin states (spin up and spin down, indicated by straight arrows). When a magnetic field is applied parallel to the nanotube, the energies of the four states can be differentiated. **b**, McEuen and colleagues[1] show that, in the absence of a magnetic field, the four states do not have equal energies, but form two distinct pairs. This suggests that the spin and orbital movement of electrons in carbon nanotubes are strongly coupled. This may provide a means of controlling spin in nanotubes electrically, which would be useful for nano-electronics applications.

In the absence of spin–orbit interactions, the electronic ground states of carbon nanotubes were thought to be four-fold degenerate — that is, at each energy level there are four states (Fig. 1). Two of these are spin states (spin up and spin down) and two are orbital states (clockwise and anticlockwise). The existence of these states can be revealed by applying a magnetic field parallel to the tube's axis. The magnetic field couples independently to the spin and orbital moments, changing the energies of the states so that they are no longer equivalent.

McEuen and colleagues' results[1] shatter the dogma of the degeneracy of carbon nanotubes.

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When they applied a magnetic field to their nanotube quantum dot, they observed the four expected states. But, surprisingly, in the absence of a magnetic field, the four states had different energies. This is most probably the result of strong spin–orbit interactions, confounding the notion that such interactions are weak in carbon. Previous studies had missed this effect, possibly because the nanotubes used in those experiments had defects that confused the data.

This study[1] is the first experimental proof of spin–orbit coupling in carbon nanotubes. But recent theoretical studies[3–6] had predicted such interactions in curved carbon structures (such as nanotubes). These theories also suggested that spin–orbit interactions in nanotubes cause electrons and holes to behave differently in their ground states. For electrons, the magnetic moment associated with spin was expected to align in the same direction as that associated with orbital movement, but for holes the moments were expected to align in opposite directions. McEuen and colleagues[1] confirmed this to be the case by studying the changes in energy of the ground states of electrons and holes in a magnetic field; their observations matched the theoretical predictions.

The authors' results raise many interesting questions. For example, the sign and size of the observed spin–orbit interactions broadly agree with theoretical calculations, but the size of the interaction is different for electrons and holes; current theories can't explain this. The observation of spin–orbit interactions in carbon nanotubes could also help to explain spin behaviour in another form of carbon — single sheets of graphite (known as graphene). In graphene, electron spin states can be retained for a long time, yet spin-polarized electrons don't move much further than they do in conventional metals[7]. This could be because of enhanced spin–orbit coupling resulting from corrugation in the graphite sheet.

If spin–orbit interactions lead to the decay of spin signals, you might expect McEuen and colleagues' results[1] to rule out carbon nanotubes as a medium for spintronics devices. But the interaction isn't strong enough to cause insurmountable problems. In fact, this effect could be exploited to allow electron spin to be manipulated by electrical means alone, a long-sought capability that would open the door to many more spintronics applications. ■

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NEUROSCIENCE

Strength in numbers

Nelson Spruston

To store information, the brain modulates synapses, which mediate communication between neurons. A closer look hints that subcellular changes in response to groups of synapses facilitate this process.

Ever since the Spanish neuroscientist Ramón y Cajal put forward his 'neuron theory'[1], synapses have been the focus of research aiming to explain learning in terms of brain plasticity, or the functional reorganization of neural pathways in response to new experiences. But synapses, which mostly spread out along highly branched neuronal processes called dendrites, are relatively tiny and have been difficult to stimulate with any precision. Using a sophisticated new method that allows precise stimulation of activity patterns generated at specific locations in a single neuron, Losonczy and colleagues[2] (page 436 of this issue) show that when clusters of synapses on a dendritic branch are stimulated simultaneously, under conditions thought to mirror brain states during learning, repeated activation leads to gradual changes in the response of the branch.

The technique used involves releasing caged molecules of the neurotransmitter glutamate at precise locations along a dendritic branch by photo-activation with a long-wavelength, pulsed laser, thus mimicking the precisely patterned input that the dendrite would naturally receive from its presynaptic partners. The free glutamate molecules can locally activate a small spot on the neuron — in this case, a dendritic spine, which is a specialized structure bearing a single excitatory synapse — with high spatial and temporal precision (of the order of 1 micrometre and 1 millisecond)[3] (Fig. 1). By rapidly scanning the laser from one spot to the next, adjacent spines can be activated almost synchronously.

In a previous study[4], the same team showed that, when stimulating several spines almost simultaneously, the responses add together

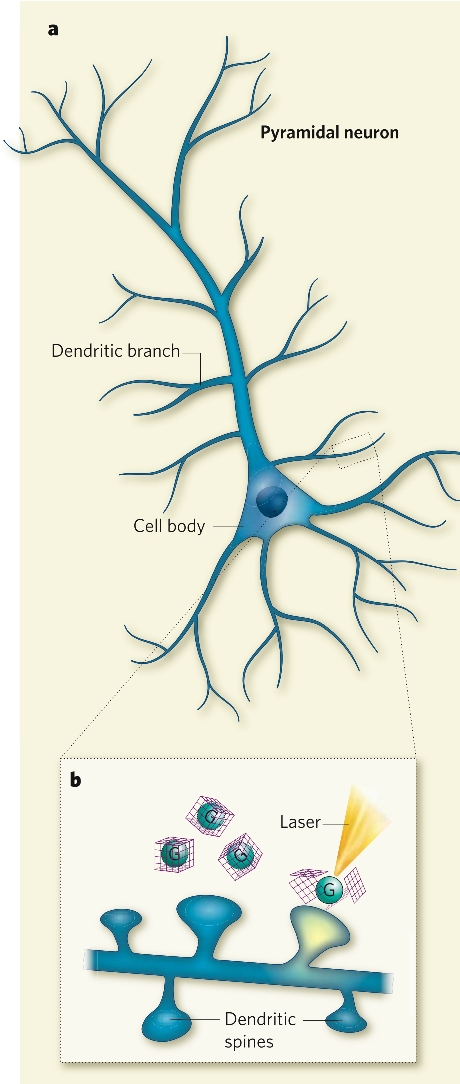

Figure 1 | A closer look at plasticity. To investigate the neural basis of plasticity at a fine scale, Losonczy *et al.*[2] activated individual dendritic branches. **a**, A typical pyramidal neuron consists of a large cell body and many dendritic branches receiving thousands of excitatory synapses, most of which are on dendritic spines. **b**, Losonczy *et al.* mimicked precisely patterned synaptic activation using laser stimulation of dendritic spines. Caged glutamate (G) is released from the cage by the laser, allowing glutamate to act locally on the dendritic spine. The laser is moved rapidly from one spine to the next to precisely mimic patterned synaptic activation. The authors found that activation of multiple spines led to a spike in the dendritic branch, and spread of the spike to the cell body could be enhanced by repeated activation under appropriate conditions.

until a threshold is reached. Beyond this threshold, activation of additional spines results in a proportionally much larger response, believed to be due to the generation of an action potential — or spike — in the dendrite. A spike consists of a fast component, mediated by voltage-gated sodium channels, and a slower component mediated by voltage-gated calcium channels and by receptors that