Coupling magnetism and mechanics on a molecular level

The magnetism of an atom or a nanometre-scale object such as a "Single-Molecule Magnet" (SMM) is governed by the laws of quantum mechanics. Various quantum effects ranging from tunnelling processes to coherent phenomena have been observed in single molecule magnets. But probing the quantum nature of these magnets remains a challenging task and requires the use of an appropriate magnetometer, preferably one with molecular dimensions itself. Encouraged by recent progress in using the quantized mechanical vibrations of carbon nanotubes to probe magnetism, we have developed a magnetometer design based on a carbon nanotube nanoelectromechanical system (a "NEMS"). Our magnetometer can measure extremely small magnetic moments.

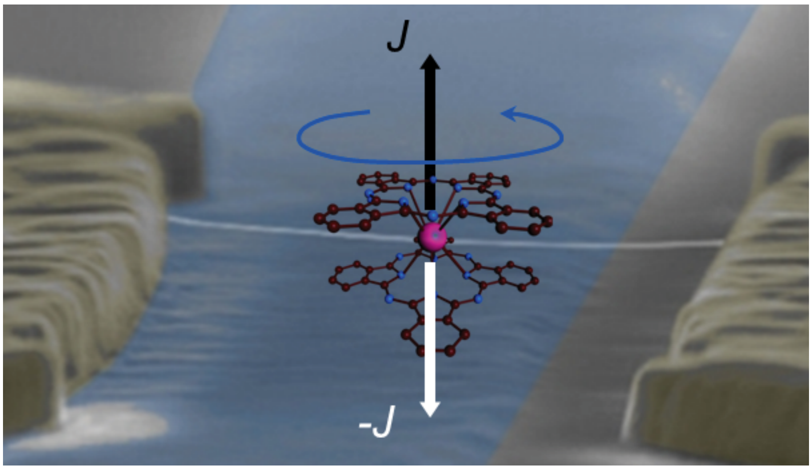

Fig. 1 :
A carbon nanotube nano-electromechanical system (NEMS) functionalized with a Single Molecule Magnet (SMM).

A Terbium Pthalocyanine molecule is grafted onto the carbon nanotube (white wire) stretched across a gap between platinum electrodes.

Due to angular momentum conservation, the magnetization reversal from *J* (black arrow) to -*J* (white arrow) in a magnetic field results in a rotation of the SMM (blue arrow). This rotation generates a quantized longitudinal phonon mode in the carbon nanotube.

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FURTHER READING

MOLECULAR SPINTRONICS USING SINGLE-MOLECULE MAGNETS
L. Bogani, W. Wernsdorfer
Nature Mat. 7, 179 (2008)

STRONG SPIN-PHONON COUPLING BETWEEN A SINGLE-MOLECULE MAGNET AND A CARBON NANOTUBE NANOELECTROMECHANICAL SYSTEM
M. Ganzhorn, S. Klyatskaya, M. Ruben, and W. Wernsdorfer
Nature Nanotech. 8, 165 (2013)

In order to achieve sensitivity at the molecular scale, the vibration of the carbon nanotube should exhibit large quality factors (*Q*) and be strongly coupled to the molecular magnet. We have indeed demonstrated strong coupling of the quantized mechanical motion of a carbon nanotube to the magnetization of a Single Molecular Magnet. This is the Terbium Pthalocyanine SMM whose properties have been introduced in the preceding article in this issue of Highlights.

The terbium molecule constitutes a rare-earth SMM where the magnetic moment is carried by a single Tb^{3+} ion. Due to the highly anisotropic 4f electron shell and the strong spin-orbit coupling of Tb^{3+}, the ground state is a well isolated magnetic ground state, a doublet $J=6$ with $J_z = \pm J = \pm 6$. This defines the magnetic behaviour of the molecule. Also, the Terbium nucleus has a spin, $I=3/2$ and each state of the ground doublet splits into four nuclear spin states by hyperfine interaction.

If the magnetization of the SMM reverses from *J* (black arrow in Fig. 1) to –*J* (white arrow), a mechanical rotation of the molecule occurs simultaneously, in order to conserve total angular momentum. This phenomenon is a quantum mechanical analogue of the classical Einstein-de Haas effect. In our experiment, we graft the molecule rigidly to a carbon nanotube (the grey wire in Fig. 1). The molecular rotation induces a strain in the nanowire and excites a quantized longitudinal phonon stretching mode in the nanotube.

It is the state of this stretching mode that we detect, using an electronic readout technique which exploits the sensitivity of a single-electron current through the nanowire to the wire's state of vibration at very low cryogenic temperatures. We perform a sensitive, indirect, non-destructive probe of the molecule's nuclear magnetic state as follows.

As we sweep an external magnetic field, the electronic spin *J* reverses via quantum tunneling at one of the four field values that identify the four possible spin states of the Terbium $I = 3/2$ nucleus. The electronic spin reversal *does not change* the nuclear spin state (see also the preceding article, page 15).

In these experiments, the electronic spin reversals are detected via the coupling to the additional mechanical degree of freedom. We find a strong coupling of the order of 1 MHz between the nanotube's mechanical degree of freedom and the molecule's electronic spin.

From an application point of view, a magneto-mechanical coupling of this magnitude should enable us to detect the magnetic state of many other SMMs. From a more fundamental point of view on the other hand, the strong coupling opens the path to coherent spin manipulation and to quantum "entanglement" between one or several electronic spins and a quantized mechanical motion.