

Coherent control of a single nuclear spin with an electric field

Over the last four decades, the size of a bit, the smallest logical unit in a computer, has decreased by more than two orders of magnitude and will soon reach a limit where quantum phenomena become important. Inspired by the power of quantum mechanics, researchers have already identified pure quantum systems that have controllable and readable discrete states, in analogy with a classical bit. In this regard, the inherent spin of an atomic nucleus with its two (or more) eigenstates is a promising candidate. We have developed a molecular transistor which allows us to write quantum information onto a single nuclear spin purely by means of an electric field, as well as to do an electronic read-out of the quantum state. This novel approach opens a path to addressing and manipulating individual nuclear spins, that is to handle information localized in a very small space (a single atom), at high speed.

The magnetic moment of a nuclear spin is ten billion times smaller than the magnetic moment of one bit of a modern hard drive. To succeed in detecting such a tiny signal, we first developed a very sensitive magnetic field sensor – the Single-Molecule Magnet (SMM) spin-transistor (Fig. 1). The heart of this device is a single metalorganic molecule. It is a terbium “double-decker” single-molecule magnet, which works as amplifier and detector for the terbium ion’s nuclear spin.

To amplify the nuclear spin signal, we make use of the “hyperfine” interaction between the terbium’s nuclear spin and its electronic spin. By mapping the nuclear spin state onto the terbium’s electronic spin state we amplify the magnetic signal by a factor of 10000. In a second stage of amplification we read-out the nuclear spin dependent magnetic moment of the terbium ion via the tunnel current through the molecular transistor. This is possible as the terbium’s electronic spin interacts strongly with the tunnelling electrons via its exchange coupling with those electrons.

In recent experiments at very low temperature (30 mK), we were able to show that the terbium’s nuclear spin can be manipulated purely by an oscillating electric field (the microwave field represented in Fig. 1). This is remarkable because the magnetic dipole associated with the nuclear spin is, to first order, by its very nature, sensitive to magnetic fields only.

Our experiment is explained by the hyperfine Stark effect, which acts as a magnetic field transducer at the

atomic level. When we apply an electric field, it modifies the electronic wave functions of the terbium ion (a “Stark Effect”). This modification in turn changes the coupling of the electronic and nuclear spins, the “hyperfine interaction”. The altered hyperfine interaction is seen by the nucleus as a change of the effective magnetic field at the nucleus. Therefore an oscillating electric field is transformed into an oscillating effective magnetic field. If the frequency of this oscillation is brought into resonance with the spacing between the nuclear spin levels, a coherent manipulation of the nuclear spin states is possible. Furthermore, the hyperfine Stark effect also allows us to shift the resonance frequency of our nuclear quantum bit (“qubit”) by means of a static electric field, which can be easily generated by applying a back-gate voltage.

The use of oscillating electric fields to manipulate nuclear spins could facilitate the integration of multiple spin-qubits in a device architecture, since electric fields are much easier to focus and to shield than magnetic fields. Moreover, the use of a static back-gate voltage to tune individual nuclear spin qubits in and out of resonance provides a possibility for addressing individual qubits using only a single-frequency microwave signal. Thus, single-molecule magnets are promising candidates for quantum information processing, and could lead to the appearance of a new field of research: molecular quantum electronics.

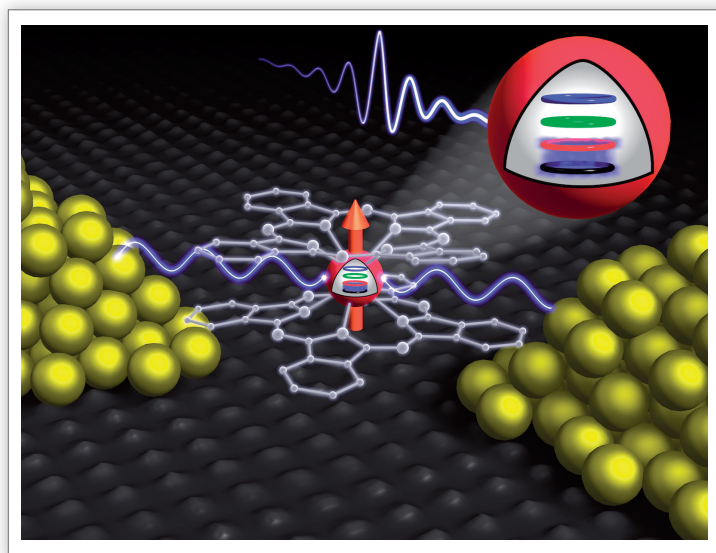


Fig. 1: The single-molecule magnet spin-transistor. The heart of the device is the terbium “double-decker” single-molecule magnet: two planar organic molecules enclosing a Terbium ion. The “magnet” is connected to two metallic leads (gold atoms) deposited on a substrate. We apply a voltage across the two contacts to establish a tunnelling current through the molecule. The read-out of the ($I=3/2$) ^{159}Tb nucleus’s four spin states (depicted in the enlargement as coloured rings) makes use of a change in this tunnelling current that occurs at well defined values of an applied external magnetic field. At these field values, the nuclear spin state is resonant with the microwave electric field pulse (blue wave).

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FURTHER READING

“Electrically driven nuclear spin resonance in single-molecule magnets”

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