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Viewpoint

Spintronics meets nanoelectromechanics

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The coupling of single spins with mechanical oscillators should lead to superior nanodevices that rely on magnetism.

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A Viewpoint on:
Macrospin Tunneling and Magnetopolaritons with Nanomechanical Interference
Alexey A. Kovalev, Lorien X. Hayden, Gerrit E. W. Bauer, and Yaroslav Tserkovnyak
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Coupling a nanoscale object with a resonator is interesting from both a practical and a fundamental point of view. On the practical side, the parametric coupling between a small system and a resonator that acts as a detector can be used to probe very small charges [1], masses [2] or magnetic moments [3]. On the fundamental side, a system with microscopic degrees of freedom coupled to a harmonic oscillator is a very important paradigm of quantum mechanics since it allows us to understand deeply the processes of measurement and amplification [4]. Studying such a coupling at the most elementary level is therefore an important goal in many fields of physics, ranging from cavity quantum electrodynamics [5] to magnetic force microscopy [3].

The basic idea of resonant detection methods is the modification of the resonance frequency of an oscillator by the system under investigation. If the resonance is sharp enough, very small changes in the properties of the system can be detected. In the context of magnetic force microscopy, for example, it was shown recently that it is possible to push this principle to its limits, down to a single magnetic moment [3]. A cantilever with a magnetic tip was used to detect a single spin embedded in a silicon dioxide slab. The cantilever, acting as the resonant detector, displays classical dynamics.

An intriguing situation arises when both the system and the resonant detector are placed in conditions that have to be treated quantum mechanically. Recently, progress in nanofabrication techniques has led to the design of artificial systems that shed new light on this question. In particular, superconducting circuits have emerged as a very powerful means to create artificial two-level systems (quantum bits) coupled to quantum harmonic oscillators (electromagnetic or electromechanic) [6, 7]. These circuits have given us an architecture with promising potential for quantum information processing in solid-state devices.

The spin degree of freedom is also an interesting resource for implementing fundamental experiments that study interactions between matter and a quantum oscillator at the most elementary level. Several recent experiments have demonstrated the possibility of manipulating and detecting the electronic spin, which can have rather long coherence times [8]. Magnetic molecules also display quantum behavior, as shown by the observation of interference effects in quantum tunneling of molecular clusters, about a decade ago [9]. However, at first glance, combining quantum oscillators with spins seems less natural than with superconducting circuit elements. Spins are indeed difficult to couple to the electromagnetic field. One has to either "engineer" an electric coupling [10] or rely on the magnetic coupling with a spin ensemble [11].

Writing in *Physical Review Letters*, Alexey Kovalev and colleagues from the US and Japan propose a new method in the quantum toolbox for manipulating single spins [12]. Rather than coupling spins to the modes of an electrical oscillator, they suggest the use of a mechanical interface for the spin of a magnetic nanoparticle or a molecule. The spin can be placed on a paddle, for instance, which actuates the torsion of a suspended beam. This coupling is realized by angular momentum conservation, where the spin of the molecule transfers angular momentum to the torsional modes of the beam. In principle, the coupling can be made arbitrarily strong by reducing the moment of inertia involved in the mechanical rotations.

An intriguing phenomenon is predicted for coupling that is so strong that it exceeds the decoherence mechanisms of the spin and the mechanical modes. The formation of these modes, called magnetopolaritons because they combine magnetic excitations and lattice deformations, means that the spin and the torsion modes of the beam are able to exchange energy coherently. Con-

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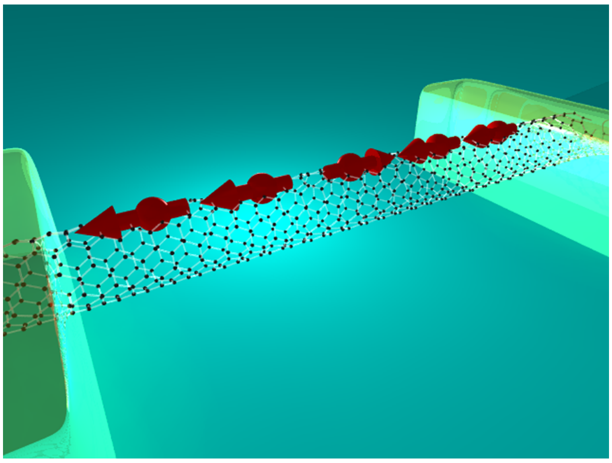

FIG. 1: A futuristic view of a potential device using the proposal of Alexey Kovalev and co-workers. Magnetic molecules (red arrows) are placed onto a suspended single-wall carbon nanotube connected to two metallic leads. The whole system is in a gradient of magnetic field. Thanks to the torsional modes of the nanotube, the molecules are able to interact by exchange of phonons.

versely, the eigenmodes of the coupled systems are hybrid in nature, i.e., superpositions of spin states with different Fock states of the oscillator. Such a phenomenon—called the strong coupling regime—is very important in quantum optics since it allows the use of all the methods of cavity quantum electrodynamics to manipulate, detect, and introduce interactions between several two-level systems [5]. Thanks to the findings of Kovalev *et al.*, a spin-spin interaction could be mediated by the virtual exchange of single torsional modes (or phonons) of the beam. Such an interaction mechanism could be used to transfer quantum information from one spin to another. Such a "phonon bus" could be exploited in the futuristic architecture represented by Fig. 1. Implementing a magnetic-field gradient using a microfabricated ferromagnetic strip in addition to the external magnetic field applied along the beam axis, one could envision in a single device—similarly to superconducting quantum bits—selective addressing of individual magnetic molecules, readout in the dispersive regime, and coupling in an "all mechanic" spin quantum bit architecture.

Alexey Kovalev and colleagues add another ingredient to this quantum recipe: the possibility of destroying these hybrid spin-phonon modes by interference effects. Such effects are particularly important for quantum tunneling in magnetic molecules. They can be used to modulate the tunnel splittings that appear in their low-energy spectrum, as demonstrated experimentally in the pioneering work by Wernsdorfer *et al.* in Fe_8 molecules [9]. The effect has its roots in the parity-induced suppression of tunneling of a given spin state [13]. Here, interferences arise from the multiple "quasi-classical paths" that the coupled spin-phonons can take to tunnel between two states involving the two lowest spin states and different Fock states. All these paths are equivalent and can therefore interfere destructively, leading to suppression of the magnetopolaritons.

Putting all these ingredients together in a single experiment appears obviously challenging. As suggested by the authors, carbon nanotubes could be promising candidates. First of all, it has recently become possible to use them in various types of rather complex hybrid structures [14, 15], and coupling them to single magnetic molecules appears realistic [14]. Furthermore, they can exhibit mechanical resonances with very high quality factors [16], which can be detected by simple electrical means. Two major issues have to be overcome however. First, one has to find efficient means to detect the small tunnel splittings that are predicted, and, at the same time, not perturbate too much the dynamics of magnetization reversal. With the advent of the nanoscale superconducting quantum interference device (nanoSQUID), which uses as building blocks single-wall carbon nanotubes [14], this goal does not seem so far away. Second, carbon nanotubes should be cooled down to the ground state of mechanical motion. Although the quantum limit has not yet been demonstrated with them, the rapid progress in the field allows for optimism [16]. The proposed engagement of spintronics and nanoelectromechanics by Alexey Kovalev and co-workers could therefore be the starting point of a happy marriage.

References

[1] R. J. Schoelkopf *et al.*, *Science* **280**, 1238 (1998).
[2] B. Lassagne, D. Garcia-Sanchez, A. Aguasca, and A. Bachtold, *Nano Lett.* **8**, 3735 (2008).
[3] D. Rugar, R. Budakian, H. J. Mamin, and B. W. Chui, *Nature* **430**, 329 ().
[4] A. A. Clerk *et al.*, *Rev. Mod. Phys.* **82**, 1155 (2010).
[5] S. Haroche and J. M. Raimond, *Exploring the quantum: atoms, cavities and photons* (Oxford University Press, Oxford, 2006).
[6] A. Wallraff *et al.*, *Nature* **431**, 162 (2004); I. Chiorescu *et al.*, *Nature* **431**, 159 (2004).
[7] A. D. O'Connell *et al.*, *Nature* **464**, 697 (2010).
[8] R. Hanson *et al.*, *Rev. Mod. Phys.* **79**, 1217 (2007).
[9] W. Wernsdorfer and R. Sessoli, *Science* **284**, 133 (1999).
[10] M. Trif, F. Troiani, D. Stepanenko, and D. Loss, *Phys. Rev. Lett.* **101**, 217201 (2008); M. Trif, V. N. Golovach, and D. Loss, *Phys. Rev. B* **77**, 045434 (2008); A. Cottet and T. Kontos, *Phys. Rev. Lett.* **105**, 160502 (2010); M. Claassen, H. E. Türeci, and A. Imamoğlu, *Phys. Rev. Lett.* **104**, 177403 (2010).
[11] Y. Kubo *et al.*, *Phys. Rev. Lett.* **105**, 140502 (2010); D. I. Schuster *et al.*, *Phys. Rev. Lett.* **105**, 140501 (2010); H. Wu *et al.*, *Phys. Rev. Lett.* **105**, 140503 (2010).
[12] A. A. Kovalev, L. X. Hayden, G. E. W. Bauer, and Y. Tserkovnyak, *Phys. Rev. Lett.* **106**, 147203 (2011).
[13] D. Loss, D. P. DiVincenzo, and G. Grinstein, *Phys. Rev. Lett.* **69**, 3232 (1992).
[14] J. P. Cleuziou *et al.*, *Nature Nanotech.* **1**, 53 (2006).
[15] C. Feuillet-Palma *et al.*, *Phys. Rev. B* **81**, 115414 (2010).
[16] G. A. Steele *et al.*, *Science* **325**, 1103 (2009); B. Lassagne *et al.*, *Science* **325**, 1107 (2009).

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Takis Kontos has been a permanent CNRS fellow at the Ecole Normale Supérieure of Paris since 2005. He obtained his Ph.D. in 2002 for studies on the interplay between the ferromagnetic and the superconducting orders in nanostructures. His main focus is now quantum transport in hybrid nanostructures and, in particular, in carbon nanotubes.

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