Good vibes: Coupling electron spin states and carbon nanotube vibrations

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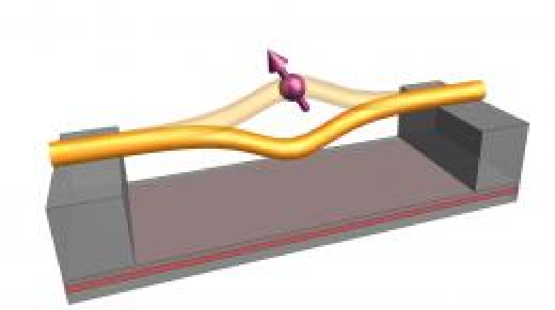

Schematic of a suspended carbon nanotube (CNT) containing a quantum dot filled with a single electron spin. The spin-orbit coupling in the CNT induces a strong coupling between the spin and the quantized mechanical motion u(z) of the CNT. Image (c) Prof. Dr. Guido Burkard, *Physics Review Letters* 108, 206811 (reproduced with permission)

(Phys.org) -- An electron's spin is separate from its motion, and is suitable for use in both highly-precise magnetic sensing as well as a qubit in quantum computing. Recently, scientists at the University of Konstanz in Germany have theoretically investigated the coupling of electron spin in carbon nanotube quantum dots, showing that the carbon nanotube's nanomechanical vibrations can significantly affect the spin of an electron trapped on it. Moreover, their findings also theoretically show that the carbon nanotube itself can be affected by the electron's spin. The researchers state that their findings have important implications for magnetic and mass nanosensors, quantum computing and other nanoscale applications.

Prof. Dr. Guido Burkard, Postdoctoral Researcher Andr´as P´alyi (now in the Department of Materials Physics at Eötvös University, Budapest) and their colleagues faced a number of challenges in their theoretical study of this phenomenon occurring at what they describe as the ultimate quantum limit. “One of the main challenges was to theoretically analyze the spin-phonon system, including the effect of its temperature,” Burkard tells *Phys.org*. “For previously known systems such as atom-photon cavities, one can safely assume zero temperature – but in a solid-state environment like ours, one needs to take into account a finite temperature.” In other words, even if experiments will be done very close to absolute zero temperature – the typical point in current research studies is one-tenth of a degree Kelvin above absolute zero – this may affect the behavior of the system.

“This was not only theoretically challenging, but also rewarding: since there hadn't been any need to do so, the relevant theoretical model, the so-called Jaynes-Cummings model, had not been studied at non-zero temperature for a driven system before, and we had a chance to enter unchartered territory here. In summary, we found that the sought-after quantum effects can still be identified at finite temperatures.” In a driven system, the resonator is actuated by an external source in the form of an antenna proximate to the resonator that couples to the charge on the carbon nanotube, causing it to move and – due to the nanotube’s inherent stiffness – vibrate. By measuring the amplitude of its oscillation, the presence of, coupling to, and (ideally) the state of the spin can be determined.

In addressing such challenges, Burkard cites a particular conceptual insight based on what the team knew from studying electron spin relaxation, or the decay of a prepared spin state, in semiconductor nanostructures known as quantum dots: that the predominant mechanism for spin relaxation involves the emission of a phonon – a quantized sound wave – into the extended solid. Spin relaxation is therefore like spontaneous emission of a photon. Spontaneous emission from atoms can be suppressed by the use of an optical cavity where in the so-called *strong coupling regime*, the photon resides in the cavity long enough to be reabsorbed and reemitted many times before it is lost – a phenomenon known as *vacuum Rabi oscillations*.

"The idea was that a nanomechanical resonator – in this case, a piece of carbon nanotube suspended over a trench – can act as the phonon cavity and allow for the analogous effect," Burkard explains. "If the resonator mode is on-resonance with the so-called Zeeman energy required for a spin flip, quantum information can transferred back and forth between the spin and the phonon; in off-resonance, a prolongation of the lifetime of the spin qubit can be achieved. The latter is therefore also something that is interesting for quantum information processing."

Mathematically, Burkard continues, the challenge was to investigate the spin-phonon system, which is both driven from outside and at finite temperature. "We used and developed two methods for this purpose: a numerical computer simulation allowed us to include all relevant effects and in particular finite temperature; and a so-called semi-classical approximation helped us to understand the main effects of the driven system at zero temperature."

Regarding next steps in their research, the scientists are currently looking into possible applications for quantum information processing, with spin playing the role of the quantum bit, or qubit. "In such a scenario," Burkard points out, "our results may lead to spin-readout schemes, as well as to new quantum-coherent spin-spin coupling mechanisms."

Burkard also outlines what would be required for the construction of physical apparatus that could test their theory – namely, a highly sensitive readout of the motion of a nanomechanical resonator. (Several labs worldwide are working on this, such as that of Leo Kouwenhoven, Herre van der Zant, and Gary Steele at the Technical University (TU), Delft, The Netherlands.) “Another requirement,” he adds, “is the ability to operate at low temperatures.”

Burkard sees a key impact of their findings being the potentially enhanced performance of nanotubes in sensing applications. ”Magnetic sensing would be based on the sensitivity of the electron spin with regard to external magnetic fields.” Since electron spin is coupled to the mechanical resonator – the vibrating carbon nanotube, which carries an electric charge by virtue of the electron confined to it – the signal could then be read out by electrical means.

“Mass sensing, in turn, would utilize a change of vibration frequency of the mechanical resonator when a small mass is deposited on it,” he continues. “The change in frequency would then affect the spin and could be read out via, for example, spin-sensitive electric transport measurable as current flowing through the nanotube.”

Burkard also sees benefits beyond the group’s own work. “Currently, there is great interest in hybrid systems for quantum information processing, as well as for studies of fundamental physics,” he notes. “In our case, it would be interesting to create quantum entanglement between the spin of a single electron and the mechanical motion of a much larger object, such as the nanotube in our current study.”

“A fundamental question in quantum mechanics,” he continues,” is about its range of applicability – that is, how large an object can be and still be in a quantum-mechanical superposition of two different places. We know that electron and single atoms behave quantum-mechanically, but objects in our macroscopic everyday world don't. The question is,” Burkard concludes, “how far we can apply quantum laws. By providing some new tools, our results may open a new door in this direction as well.”

More information: *Spin-Orbit-Induced Strong Coupling of a Single Spin to a Nanomechanical Resonator*, *Physics Review Letters* 108, 206811 (18 May 2012), doi: 10.1103/PhysRevLett.108.206811

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