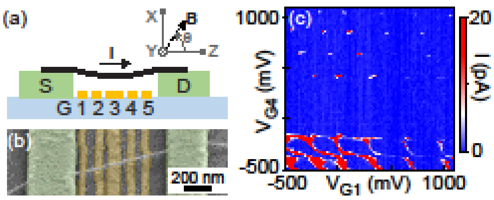
Final Report: NANOTUBEQUBIT

Brief summary

The aim of this project was to develop qubits based on spins in carbon nanotubes and molecules. We have extended the coherence time of the carbon nanotube qubit from 60 ns to 200 ns [1], and developed new tuneable readout technology for spin qubits [2]. Furthemore, the scope of my work has expanded from nanotube qubits to other kinds of quantum devices. The central theme is using carbon nanomaterials to exploit quantum states of spin and motion. I use techniques of nanofabrication, cryogenics, and electronics.

Results

<u>Controlling a carbon nanotube qubit via electron spin resonance</u>



During my postdoc in Delft, I implemented the first spin qubit in a carbon nanotube. I have now translocated this technology to Oxford. A longstanding mystery in nanotube quantum devices is the rapid decay of spin states. We have shed light on this mystery by measuring carefully the effect of two relaxation processes: spin-orbit coupling and hyperfine coupling. Our results indicate that hyperfine coupling is responsible for the spin dephasing [1].

<u>Radio-frequency optomechanics with a vibrating carbon nanotube</u>

Cavity optomechanics exploits resonant confinement of electromagnetic fields to measure and manipulate moving objects with exquisite precision. Recently, even quantum effects of motion have become accessible, inspiring new technologies for sensing, amplification, and frequency conversion. Research until now has mainly used micro-fabricated resonators; however, these generally suffer a reduction in quality factor as they are miniaturised towards the quantum regime.

Vibrating carbon nanotubes offer a unique combination of high resonant frequency, large quantum zero-point motion, and high quality factor. Until now, nanotube resonators have mainly been measured via electrical current. More sensitive detection comes from optomechanical readout, which measures displacement via coupling to an electromagnetic cavity. We have demonstrated the first resonant optomechanical measurement of a vibrating nanotube, and shown that the sensitivity is capable of approaching the quantum limit [3].

<u>A spin resonance atomic clock transition in the endohedral fullerene $^{15}N@C_{60}$</u>

The same properties that make carbon nanomaterials so attractive for hosting qubits are also promising for other quantum applications. One such application is atomic timekeeping. Atomic clocks are among the most precise instruments ever built. There is a major need to reduce size, weight, and power consumption to incorporate them into portable equipment and enable jam-resistant navigation, communication, and radar. However, there are challenges to miniaturizing the vacuum and optical elements of vapour-based clocks.

We are developing a novel concept using nature's own atom trap – endohedral fullerene molecules. In these molecules, single nitrogen atoms float in the centre of a fullerene cage. Because the cage protects the nitrogen, the spin resonances are extremely sharp. We have recently demonstrated the existence of a clock transition, where the transition frequency is (to first order) immune to magnetic field noise [4].

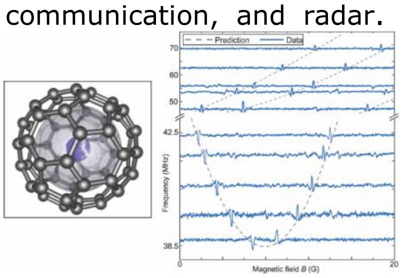


Figure 1 Left: N@C60 molecule. Right: Clock transition measured in spin resonance.

Socioeconomic impacts.

My work on <u>spin qubits</u> has potential to contribute to the field of quantum computing. If built, a quantum computer would make it possible to simulate some chemical reactions and materials that are beyond classical computers. Nobody knows what the ideal material for a quantum computer is. Leading candidates, each with tens of millions of euros worth of investment from governments and industry, include superconducting junctions, trapped ions, and spins in semiconductors. Within the field of semiconducting quantum computing, gallium arsenide and silicon materials have continued to advance rapidly, and it is unlikely that carbon nanotubes will be the host material for future quantum devices. However, the associated tools such as radio-frequency readout are applicable to other kinds of materials, including other semiconductors.

Nanomechanical resonators can find use as force microscopy probes. For example, a very sensitive probe could perform magnetic resonance imaging of single molecules. In this application, the noise is set by the thermal motion of the probe, and so high resolution sensing requires a light, compliant, high quality spring that works at low temperature. Nanotubes provide exactly this capability.

Affordable chip-scale atomic clocks would have wide application in navigation, communication, and sensing, for example in jam-resistant GPS. The ability to lock stably to the carrier frequency makes navigation possible even in environments where the signal is degraded, such as in tunnels, near dense buildings, or on battlefields. At present the leading technology is based on miniaturised vapour cells, but these are expensive, power, hungry, and too large to fit inside mobile phones. The endohedral fullerene clock is entirely electronic and works with a solid-state or liquid-state active medium. It therefore has the potential to fit on an integrated circuit, and thus be used in a wide variety of portable electronics.

Conclusions

The state-of-the art in nanotube qubits, including my own work, is still far from the elading materials for quantum computing. With regard to one of the most important figures of merit, the qubit dephasing time, there is evidence that it could be extended using isotopically purified material. Even if this can be achieved, there are still many challenges to be overcome to make a nanotube quantum computer a useful technology, including developing scalable fabrication and suppressing the sensitivity of spin qubits to charge noise.

[1] T. Pei, A. Pályi, M. Mergenthaler, N. Ares, A. Mavalankar, J. H. Warner, G. A. D. Briggs, and E. A. Laird, Phys. Rev. Lett. **118**, 177701 (2017).

[2] N. Ares, F. J. Schupp, A. Mavalankar, G. Rogers, J. P. Griffiths, G. A. C. Jones, I. Farrer, D. A. Ritchie, C. G. Smith, A. Cottet, G. A. D. Briggs, and E. A. Laird, Phys. Rev. Appl. **5**, 34011 (2016).

[3] N. Ares, T. Pei, A. Mavalankar, M. Mergenthaler, J. H. Warner, G. A. D. Briggs, and E. A. Laird, Phys. Rev. Lett. **117**, 170801 (2016).

[4] R. T. Harding, S. Zhou, J. Zhou, T. Lindvall, W. K. Myers, A. Ardavan, G. A. D. Briggs, K. Porfyrakis, and E. A. Laird, arXiv 1705.04817 (2017).