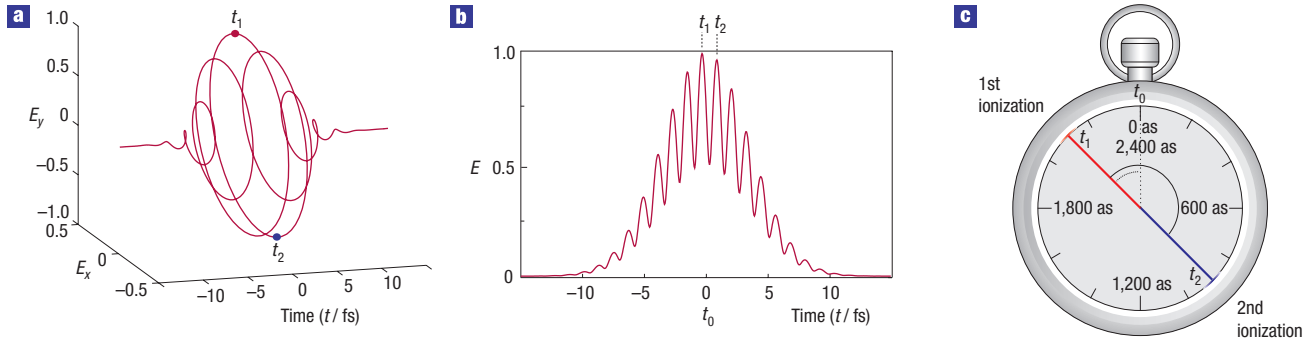


**Figure 1** The attosecond stopwatch. **a**, Temporal evolution of the electrical-field vector of an elliptically polarized few-cycle laser pulse with stable waveform (shown here for an ellipticity of 0.5). **b**, Electric field $E(t) = \sqrt{E_x^2(t) + E_y^2(t)}$ of the laser pulse. **c**, Principle of attosecond angular streaking: ionization takes place at times when the field amplitude reaches a maximum. This happens two times per optical light cycle; for the case depicted in panel **b** at times $t_1$ and $t_2$. For a known waveform of the electric field (that is, if $t_0$–$t_1$ is known), the absolute time at which ionization occurs can be determined. The ionization time is reflected by the emission angle of electrons, which changes with time like the hand of a stopwatch. For 725-nm light the watch hand undergoes a full circle in ~2,400 attoseconds.

With the waveform of the infrared pulse precisely known, the launched electron wavepackets can be timed absolutely with the 'attosecond stopwatch' (Fig. 1). For pulses with constant carrier frequency, an independent measurement of the phase of the infrared waveform should already provide this information and seems straightforward to implement. A full retrieval of the infrared waveform, without any assumptions on the time dependence of the carrier frequency, would be achievable with the use of attosecond light pulses such as in conventional streaking measurements.

Attosecond angular streaking also holds promise for providing temporal information on multi-electron emission. In conjunction with the use of coincidence detection techniques, it might be applied to measure the correlation between electrons and used to measure the tunnelling time of electrons with high precision. In its first real-time observation, optical-field-induced tunnelling was intertwined with a preceding shake-up of electrons, and hence only an upper limit of 380 as for the overall duration of both processes could be obtained[8]. To date, the time associated with tunnelling alone — one of the most fundamental processes in quantum mechanics — has not been measured and keeps issuing a grand challenge to attoscience. Attosecond angular streaking affords promise for rising to this challenge.

## References

1. Eckle, P. *et al. Nature Phys.* **4,** 565–570 (2008).
2. Baltuska, *A. et al. Nature* **421,** 611–615 (2003).
3. Itatani, J. *et al. Phys. Rev. Lett.* **88,** 173903 (2002).
4. Kienberger, R. *et al. Nature* **427,** 817–821 (2004).
5. Sansone, G. *et al. Science* **314,** 443–446 (2006).
6. Cavalieri, A. L. *et al. Nature* **449,** 1029–1032 (2007).
7. Dietrich, P., Krausz, F. & Corkum, P. B. *Opt. Lett.* **25,** 16–18 (2000).
8. Uiberacker, M. *et al. Nature* **446,** 627–632 (2007).

QUANTUM DOTS

# Time to get the nukes out

The ability to electrically control spin dynamics in quantum dots makes them one of the most promising platforms for solid-state quantum-information processing. Minimizing the influence of the nuclear spin environment is an important step towards realizing such promise.

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Intense theoretical efforts have produced algorithms that harness the potential power of quantum computing[1]. Despite similarly vigorous experimental efforts, we have yet to identify a clear choice of the best physical platform on which a future quantum computer might be implemented. One of the more promising solid-state candidates encodes quantum information (or qubits) in the spin of electrons confined to semiconductor quantum dots[2]. Quantum dots are nanostructures that can be used to trap single charges. Owing to their small size, quantum dots exhibit many properties of real atoms. They have discrete electronic energy states, obey Hund's rules, and share electrons with neighbouring dots in a manner similar to conventional molecular bonding[3]. But unlike real atoms, the potential that confines electrons to a quantum dot can be electrically tuned, enabling the quantum dynamics occurring within them to be controlled by the voltage on a nearby gate. Moreover, quantum dots can be readily fabricated, and potentially monolithically integrated into larger systems, using existing semiconductor technologies. Such versatility has led to a great deal of success in preparing, manipulating and measuring the quantum spin states of semiconductor quantum dots[4]. But there's a catch. The degree of interaction of these spins with their environment, and in particular with the nuclear spins of the quantum dots in which they are confined, is a major cause of decoherence and loss of quantum

information. Fabrication of quantum dots in materials with zero nuclear spin could provide a solution to this problem.

Some of the most advanced experiments in the quantum control of spin have been performed using quantum dots made from III–V semiconductors, such as gallium arsenide. All of the naturally occurring Ga and As isotopes have a nuclear spin of 3/2. In a typical GaAs quantum dot, the electronic wavefunction overlaps with roughly one million spin-3/2 lattice nuclei through the contact hyperfine interaction. Owing to this interaction, the electron spin experiences a fluctuating 'hyperfine field', which leads to spin dephasing on a 10 nanosecond timescale[5]. Singlet–triplet decoherence-free subspaces and spin-echo error correction provide some protection from the hyperfine interaction, but it is becoming increasingly clear that for a practical spin-based quantum device to function well, the nuclear spin dephasing mechanism must be suppressed or completely eliminated[5,6].

Recent advances in the ability to locally gate carbon nanotubes (CNTs) and Si/SiGe heterostructures, without introducing charge noise or gate leakage currents, have made it possible to create coupled quantum dots in materials that are effectively free of the effects of nuclear spin[7]. Two papers in this issue explore systems that are expected to have longer spin coherence times than GaAs. On page 536, Jørgensen and co-workers use tunnelling spectroscopy to resolve singlet and triplet spin states in CNT double quantum dots — a first step in quantum control of a CNT singlet–triplet qubit[8]. And on page 540, Shaji *et al.* present a demonstration of what they refer to as "lifetime-enhanced transport" in a top-gated double quantum dot made from a Si/SiGe heterostructure[9]. Both of these systems are largely composed of spinless nuclei; of their naturally occurring isotopes only ~1.1% of carbon, 4.7% of silicon and 7.7% of germanium have a non-zero spin. Furthermore, it is possible to isotopically purify these compounds, virtually removing any nuclei with non-zero spin.

Using tunnelling spectroscopy, Jørgensen *et al.* perform the first measurement of the singlet–triplet splitting in a CNT double quantum dot (see Fig. 1a). The two-fold sub-band degeneracy of this material, combined with the spin-state degeneracy, leads to a four-fold shell structure in CNT single quantum dots. Jørgensen *et al.* expand on previous work by measuring the shell structure in gate-defined CNT double quantum dots. The authors are able to tune gate voltages between regions where each dot displayed a four-fold shell-like electronic structure (arising from a combination of both spin and orbital degeneracy), and a two-fold shell-like electronic structure (arising from spin degeneracy only). Singlet and triplet states were identified by observing the effect of a magnetic field on the double-dot charge-stability diagram. Furthermore, this allowed the measurement of the energy difference between the singlet and triplet states, or the exchange energy, and demonstrated the ability to tune this energy by changing the overlap of the electronic wavefunctions. The ability to identify singlet and triplet states, and to control the exchange energy between two electrons, is key to the Loss–DiVincenzo spin–qubit architecture and is an important first step towards coherently controlling the spin degree of freedom in CNT double quantum dots[2].

However, identifying a quantum state is of little use if it relaxes or decoheres faster than it can be controlled. To this end, Shaji *et al.* make a first attempt to measure triplet–singlet relaxation times in a Si/SiGe double quantum dot[9]. Their strategy is to examine transport through the double quantum dot, as previous transport measurements in GaAs double quantum dots were shown to be sensitive to the nuclear spin environment[10]. Neglecting spin for the moment, at positive bias, electron transport through the double quantum dot proceeds via the sequential tunnelling sequence (1,0)→(1,1)→(2,0)→(1,0) (Fig. 1b). Here $(N_L,N_R)$ denotes the number of electrons trapped in the left and right quantum dots respectively. But when spin is included, the inter-dot charge transition, (1,1)→(2,0), can be blocked depending on the spin state of the two electrons. Such 'spin blockade' occurs when a double dot in the (1,0) occupation state loads a second electron and forms a (1,1) triplet state, denoted T(1,1) in ref. 9. Tunnelling from T(1,1) to the (2,0) singlet ground state, S(2,0), is forbidden due to a spin selection rule, as first discovered by Ono *et al.*[4]

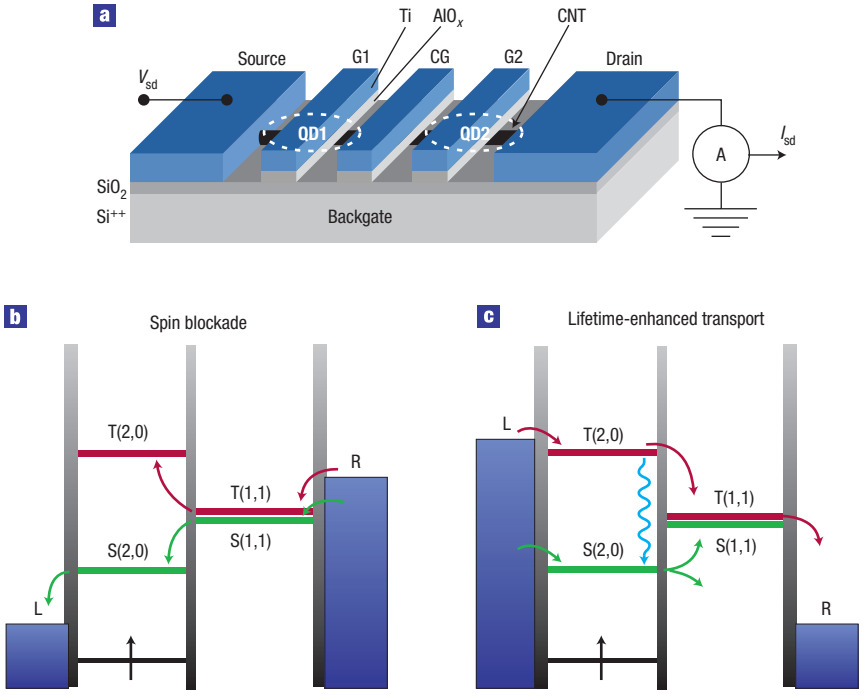


**Figure 1** Double quantum dots realized in a CNT and in Si/SiGe-based heterostructures. **a**, The system studied by Jørgensen *et al.*[8] consists of a single-wall CNT contacted by source and drain electrodes. Local depletion gates G1, G2 and CG define the double quantum dot. Gates G1 and G2 control the left and right quantum dots, and gate CG tunes the tunnel coupling between the dots. **b**,**c**, The system described by Shaji *et al.*[9] is similar in arrangement (consisting of two quantum dots controlled by a series of nearby gates) but formed in a Si/SiGe heterostructure, the electronic structure of which is shown under positive-bias (**b**) and negative-bias (**c**) conditions. Under positive bias, electrons entering the singlet state S(1,1) (green) from the right electrode can readily tunnel into the singlet state S(2,0) and flow rapidly out of the left contact. But under the same conditions, electrons entering the triplet state T(1,1) (red) are prevented from taking a similar path to the left contact (via the energetically higher T(2,0) state), resulting in spin-blockade. Electrons flow in the opposite direction through the double dot under negative bias conditions (**c**). If an electron injected from the left lead forms S(2,0), current will be blocked, because S(1,1) is higher in energy. However, an electron injected from the left lead that forms a T(2,0) state can then sequentially tunnel to the T(1,1) state. The key to this mode of transport is very slow relaxation from the preferentially loaded T(2,0) state to the blockaded S(2,0) state, hence the name lifetime-enhanced transport.

Shaji *et al.* explore electron transport for the opposite sign of bias voltage, where charge transport proceeds in the tunnelling sequence (2,0)→(1,1)→(1,0)→(2,0), as illustrated in Fig. 1c. In contrast with measurements in GaAs quantum dots, Shaji *et al.* find that their Si/SiGe double dot, when operated in this regime, unexpectedly transfers electrons with almost no drop in the measured conductance. The authors give two requirements for observing this effect: the probability of loading an electron into the T(2,0) state must be much higher than the S(2,0) state, and the relaxation from T(2,0) to S(2,0) must be very slow. If either condition is not met (as in previous studies), then the system will fall back into a S(2,0) state, and current will be blocked. Owing to the second requirement above, the authors call this mode of transport lifetime-enhanced transport, or LET, because it is made possible by the long triplet-state lifetime. Although they do not directly measure the triplet–singlet relaxation time, the analysis of the data using a rate-equation model sets a lower bound on the relaxation time of 16 μs.

Rapid progress in GaAs quantum dots has been made possible by decades of continual improvement of the GaAs/AlGaAs materials system. The results presented in this issue demonstrate the future potential of carbon- and silicon-based quantum devices. Spin-relaxation times exceeding 100 milliseconds have been reported for GaAs quantum dots[4]. The 16-μs relaxation time reported for the Si/SiGe system is a far cry from the results obtained so far in GaAs, but if theory and measurements of spin coherence in Si/SiGe bulk systems are any indication, there is great potential for electron spin qubits in a nuclear-spin-free quantum world[4].


## References

1. Deutsch, D. *Proc. Roy. Soc. Lond. A* **400,** 97–117 (1985).
2. Loss, D. & DiVincenzo, D.P. *Phys. Rev. A* **57,** 120–126 (1998).
3. Kouwenhoven, L. P. & Marcus, C. M. *Phys. World* **11,** 35–39 (1998).
4. Hanson, R., Kouwenhoven, L. P., Petta, J. R., Tarucha, S. & Vandersypen, L. M. K. *Rev. Mod. Phys.* **79,** 1217–1265 (2007).
5. Petta, J. R. *et al. Science* **309,** 2180–2184 (2005).
6. Levy, J. *Phys. Rev. Lett.* **89,** 147902 (2002).
7. Mason, N., Biercuk, M. J. & Marcus, C. M. *Science* **303,** 655–658 (2004).
8. Jørgensen, H. I. *et al. Nature Phys.* **4,** 536–539 (2008).
9. Shaji, N. *et al. Nature Phys.* **4,** 540–544 (2008).
10. Ono, K. & Tarucha, S. *Phys. Rev. Lett.* **92,** 256803 (2004).


WILLIS LAMB

# Shift to quantum electrodynamics

AIP EMILIO SEGRE VISUAL ARCHIVES

Willis Lamb was, until his death on 15 May 2008 aged 94, the longest surviving Nobel laureate in physics. He received his prize in 1955 "for his discoveries concerning the fine structure of the hydrogen spectrum" — specifically, the Lamb shift.

Born in Los Angeles in 1913, Lamb studied at the University of California, Berkeley, under Robert Oppenheimer, before joining Columbia University in 1938. His wartime experience in the Columbia Radiation Laboratory, working on microwave radar, was to inspire his lasting contribution to physics.

Throughout the 1920s, great strides had been taken in developing the theory of quantum mechanics, the greatest milestone being arguably the Dirac equation, published by Paul Dirac in 1928. Although the broad quantum picture was taking shape, many details were lacking. One of these concerned the prediction arising from Dirac's theory that the $2S_{½}$ and $2P_{½}$ energy levels in the spectrum of hydrogen should be degenerate. In the years before the outbreak of war, numerous attempts to test this experimentally had failed. However, Lamb "just knew" — as he later recalled (J. Mehra & H. Rechenberg in *The Quantum Theory of Planck, Einstein, Bohr and Sommerfeld* Vol. 6, p1037, Springer, 1982) — "that the energy levels of hydrogen were not quite what they were predicted by Dirac to be". In 1947, he proved it.

Exploiting the advances in microwave technology made during the war, Lamb devised, and conducted with Robert Retherford, microwave experiments of sufficient sensitivity to reveal at last the shift in energy between the $2S_{½}$ and $2P_{½}$ levels. Such was the importance of his result that he was invited to present it on the opening day of the Shelter Island conference, on 2 June 1947. Shelter Island was a defining moment in the history of physics in the USA: for the first time in years, an elite group of theorists gathered, free from the restrictions of wartime, ready to kick-start a programme of research that would tackle some of the most fundamental aspects of physics.

Oppenheimer, one of the delegates, reportedly considered the conference to be the most successful he ever attended. Something of the intensity of discussion, particularly among the young turks, is captured in photographs of the time: pictured here, left to right, are Lamb, Abraham Pais, John Wheeler, Richard Feynman, Herman Feshbach and Julian Schwinger. Suitably inspired, it was Hans Bethe, riding home on the train from the conference, who took the first step in recognizing the significance of the Lamb shift in quantum electrodynamics — a theory that, in the hands of Feynman, Schwinger and others, would become the most robust and well tested in all of physics.

**Alison Wright**