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Quantum Measurement and Control of Single Spins in Diamond

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linkage found in bacterial and eukaryotic lipids (*16*, *17*). The divergent planctomycete group, the Anammox bacteria, is so far, the only organism with membranes containing both ether- and ester-linked lipids.

The PVC bacteria are indeed a curiosity and their phylogenetic location in the Tree of Life is unclear. Although these features could be the result of lateral gene transfer events, convergence, or a complex universal ancestor, their intermediate nature can be considered a more parsimonious scenario. The possibility of a fusion scenario remains disputed (*18*). More evolutionary scenarios are likely to unfold—and be debated—as more bacteria and archaea are discovered and characterized. Although division into three domains of life remains the norm (*19*), the PVC superphylum may reflect continuity between the three domains, blurring their distinction.

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PHYSICS

Quantum Measurement and Control of Single Spins in Diamond

Changes in the state of a single spin at a defect in diamond, read out from optical measurements, could be used in quantum sensing and computing.

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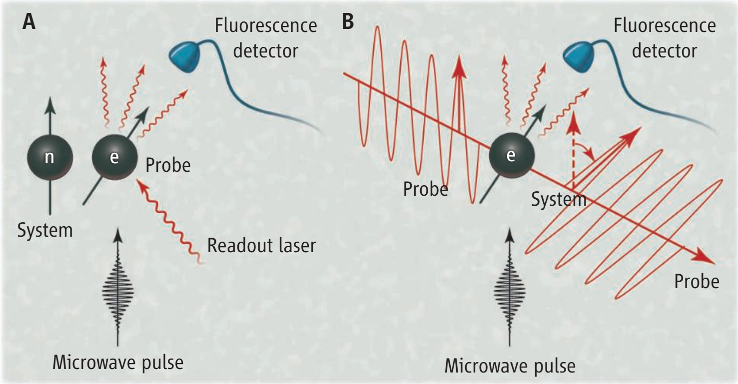
One of the important advances in quantum physics during the past 25 years has been the development of an ability to make repeated measurements on a single quantum system. This capability began in ion-trapping experiments in the early 1980s (*1*) and was exploited in studies of the number of photons in a microwave cavity in the early 1990s (*2*). For quantum computing applications, solid-state implementations provide robust platforms, and phase measurements of single quantum bits in superconducting circuits have been made (*3*). Neumann *et al.* (*4*), in a recent issue, and Buckley *et al.* (*5*), on page 1212 of this issue, now report the repeated measurement of single spins in a particular type of defect in diamond—the nitrogen-vacancy (NV) color center—through changes in its fluorescence.

Quantum effects were discovered by making measurements on systems that are large ensembles of atomic systems where quantum and classical noise can be confused. For example, the explanation of the thermal spectrum of blackbody radiation necessarily combines Planck's hypothesis, restricting the energies available to an individual oscillator with classical thermodynamics in order to correctly describe measurements made on a macroscopic system. Even Schrödinger was confused on this point (*6*).

When repeated measurements are made on one and the same quantum system, the need to correctly update the description of the quantum state of the measured system, conditional on the information obtained, becomes essential. In a long sequence of measurements, the state at the *n*th step can only be assigned if we know the initial state, the results of all preceding measurements, and the certainty (efficiency) of the measurement.

In a single spin-½ system prepared in an equal superposition of spin-up and spin-down, an efficient measurement allows the assignment of that state as spin-up. However, if the measurement has more uncertainty, the post-measurement state would need to contain some component of spin-down. The new assignment would need to reflect how good the measurement actually is.



Reading out the state of single spins. Two measurements of spin in a single nitrogen-vacancy (NV) diamond color center are depicted. (**A**) In the quantum nondemolition measurement (QND) scheme of Neumann *et al.*, the nuclear spin of a nitrogen atom is measured by first coupling it to an electron spin of the nearby NV center with an appropriate nuclear spin microwave pulse. The electron spin is then read out optically by means of electron spin–dependent fluorescence. The nuclear spin state is measured in a "single-shot" experiment with a probability of success greater than 90%. (**B**) In the scheme of Buckley *et al.*, the electron spin of the NV ground state is measured using the Faraday effect. The polarization of an optical probe field is rotated by an angle conditional on the electron spin. This is not a single-shot measurement but requires many samplings. A Hahn microwave pulse probes the decoherence of the electron spin caused by unwanted interactions of the electron spin with its environment.

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Repeated inefficient measurements on a single quantum system are easily described in the modern approach to quantum measurement that has its roots in the efforts to detect gravitational waves. In that setting, the idea of a quantum nondemolition measurement (QND) was developed. A sequence of QND measurements leads to a near-deterministic sequence of results. The noise added by a measurement does not dynamically feed back to the measured variable. Constants of the motion must be used as QND variables, and they need to remain constants of the motion when the measurement probe is coupled into the system. By contrast, in a non-QND experiment, any attempt to measure the position of a free particle very accurately would introduce a great deal of noise into its momentum. Changes in momentum couple back into the particle's position, so this noise contaminates future measurements of position.

The quantum control of single quantum systems requires three capabilities: state preparation, unitary control of the state, and quantum-limited measurement. In the case of NV diamond, the target quantum system is either a single electron or a nuclear spin. Usually, state preparation is achieved by passively cooling a system so that it relaxes to a ground state from which thermal excitation is improbable. Nuclear and electron spins in diamond can be polarized and remain so for sufficiently long times for these experiments, even at room temperature. Unitary control ensures that any operations on the system do not erase information about the quantum state.

A quantum-limited measurement is one that is efficient; that is, the signal-to-noise ratio is primarily determined by the quantum noise in the measured system itself and does not need many repeated trials to average out the noise added by the measurement apparatus—it yields a result in a "single shot." Until now, however, there has been no way to make efficient quantum measurements on the spins in a single NV center. Both of the experiments of (*4*, *5*) implement a QND measurement of a single spin—a nuclear spin in the case of Neumann *et al*., and an electron spin in the case of Buckley *et al.*

In the Neumann *et al*. experiment, the measured system is a single nuclear spin of nitrogen at an NV center, while the first stage of the measurement probe is the associated electron spin (see the figure, panel A). When the NV center is excited by a microwave pulse, the nuclear spin can flip the associated NV electron spin, conditional on the nuclear spin being spin-down, while remaining unchanged itself. The electron spin is read out optically by means of spin-dependent fluorescence, very much like the earliest experiments on quantum jumps in ion traps. The Neumann *et al*. experiment approaches an efficient measurement.

In the Buckley *et al*. study, the measured system is the electron spin of the NV, and the probe is the polarization of a laser field (a Faraday effect; see the figure, panel B). This experiment measures the electron spin directly and also uses spin-dependent fluorescence. Their approach has the advantage of enabling very accurate characterization of the nature of the interaction between the spin and the light. However, unwanted interactions in the diamond crystal cause this spin not to be a strict QND variable, so their measurement is not efficient and causes unwanted decoherence. The Buckley *et al*. experiment required tens of thousands of repeated samplings, and the signature of unwanted decoherence is the decay of a coherent oscillation signal created by Hahn microwave pulses. In the case of the efficient measurement of Neumann *et al.*, the signature of such unwanted interactions appear as "quantum jumps" in the observed fluorescence signal in a single trial.

These two experiments bode well for future quantum computing schemes that use NV diamond, but promise a more immediate spin-off for quantum sensing applications such as magnetometry. This capability could have an impact in biology and chemistry, especially if NV centers in diamond are used as nanocrystal probes (*7*). These experiments point to a future quantum sensing technology.

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NEUROSCIENCE

Lynx for Braking Plasticity

Michael J. Higley and Stephen M. Strittmatter

Knocking out the *Lynx1* gene restores plasticity in the visual cortex of adult mice.

The juvenile brain exhibits a high capacity for plasticity and repair that is severely restricted in adulthood. In young mammals, for instance, classic experiments have shown that closing one eye for several days (monocular deprivation) leads visual cortex neurons to shift their responses toward sensory inputs originating from the other, nondeprived eye (*1*). In adults, however, such plasticity in ocular dominance, while not eliminated, is strongly restricted. This knowledge gap has medical implications, because the restoration of juvenile plasticity in injured or dysfunctional adults has the potential to allow recovery of neurological performance. On page 1238 of this issue, Morishita *et al.* (*2*) identify one brake on visual cortex plasticity in adults: Lynx1, a protein that inhibits nicotinic acetylcholine receptors (nAChRs). By eliminating the gene that expresses Lynx1 in mice, the researchers were able to create adult animals that exhibited visual cortex plasticity similar to that exhibited by juveniles.

Nicotinic receptors are present throughout the nervous system. They form "channels" that enable small ions to pass through neuronal membranes, and have "gates" that are opened by acetylcholine, a common neurotransmitter. Lynx1 is similar to snake venom proteins that inhibit nicotinic receptors, and deleting the *Lynx1* gene is known to increase cholinergic neurotransmission (the activity of acetylcholine) (*3*). Morishita *et al.* noted that, in juvenile mice, Lynx1 expression increases as the critical period for visual cortex plasticity closes. To better understand the role of Lynx1, they created knockout mice that lacked the *Lynx1* gene. Then, they used electrophysiological methods to measure the effect of monocular deprivation on neocortical ocular dominance (the eye preference of single cortical neurons) in both the knockout mice and wild-type mice that still expressed Lynx1. After 4 days of monocular deprivation, 60-day-old adult knockout mice exhibited plasticity that matched that of 30-day-old juvenile wild-type mice; in contrast, adult wild-type mice did not show such plasticity. Subsequent experiments with drugs that blocked nicotinic receptors produced results

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