the experiment. Lundeen and colleagues have strikingly demonstrated that quantum tomography serves as the ideal method for translating our assembled experiment into the language of quantum theory. ❐

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SPINTRONICS

Electric spin orchestra

Localized electron spins can be manipulated electrically through electric-dipole spin resonance. The ensemble of mechanisms involved has now been brought under the baton of a unifying theoretical description.

Yasuhiro Tokura

Central to any applications in spintronics and spin-based quantum-information processing is the ability to control the spin degree of freedom and, in particular, transitions and superpositions between 'spin-up' and 'spin-down' states of electrons. One way of achieving this is through electron spin resonance: an oscillating magnetic field is applied with a frequency tuned to the Zeeman energy splitting of localized states, induced by an additional static magnetic field. For practical purposes, though, the use of electric fields would be more desirable as their high-frequency, on-chip localized generation is more readily achieved than for magnetic fields. However, unlike magnetic fields, which couple directly to the spin degree of freedom, electric fields couple directly only to the charge. There are, nevertheless, indirect ways to 'entangle' charge and spin such that electron spins can be controlled by electric fields. This was recently shown in three independent experimental demonstrations[1–3] of electric-dipole spin resonance (EDSR) — the electrical analogue to electron spin resonance — in quantum dots. Remarkably, it was found that the indirect interaction between the applied oscillating electric field and the localized electron spins in these experiments is mediated by three very different mechanisms. Writing in *Physical Review B*, Emmanuel Rashba now provides a unifying theoretical description of the three observed types of EDSR, and also describes the crucial role of nuclear spins in determining their properties[4].

The first main ingredient in the three experimental demonstrations of EDSR was the sensitive ability to create, manipulate and detect single electron spins localized in each of the dots in an electrostatically defined GaAs double-dot system subject to a static magnetic field[1–3]. The second crucial ingredient was the application of an oscillating electric field to induce transitions between spin-up and spin-down states in one of the dots (Fig. 1a) and the subsequent selective charge detection via the Pauli spin-blockade phenomenon — essentially, electrons can only tunnel when the electron spins in the double-dot system are in an anti-parallel configuration. The probability for the electrically induced spin-flip transition, *P(t)*, is an oscillating function of the burst time (the duration of the applied oscillating electric field), a phenomenon known as Rabi oscillations. Since the charge transfer through the double-dot system is directly related to *P(t)* owing to the spin-blockade mechanism, a carefully executed transport measurement should therefore reveal signatures of spin resonance.

The third crucial prerequisite for the observation of EDSR is a mechanism that mediates the coupling between the applied electric field and the electrons' spin degree of freedom. The three experiments reported in refs. 1–3 relied on entirely different mechanisms. In the experiment by Novack and co-workers[1], the mediating interaction was based on spin–orbit (SO) coupling, the most 'traditional' way to entangle spin and charge in semiconductor spintronics. An alternative coupling mechanism can be realized by the use of an inhomogeneous magnetic field, as observed by Pioro-Ladrière and co-workers, in an experiment where a slanted magnetic field was explicitly generated on-chip by a micro-magnet[2].

A third, more intricate, way to entangle the spin and charge degrees of freedom is via the hyperfine interaction between the electron spin and the nuclear spins of the atoms in the quantum dots, as demonstrated in the EDSR experiment conducted by Laird and colleagues[3]. The basic mechanism there is similar to the inhomogeneous magnetic-field case of Pioro-Ladrière *et al.*[2]. However, the inhomogeneous magnetic field that the electron spins experience originates intrinsically from the so-called 'Overhauser field', an effective magnetic field caused by fluctuations of the nuclear spins (Fig. 1b).

The unifying approach outlined by Rashba[4] is able to describe the SO, magnetic and hyperfine-mediated EDSR phenomena in quantum dots. Using a semi-classical mean-field theory, the presented theoretical framework describes the spin dynamics of quantum dot electrons in a sea of nuclear spins. The mean-field character of the theoretical description essentially means neglecting the quantum nature of the nuclear spins and focusing solely on the contribution of the single-site pair correlation function of the nuclear angular momenta. This assumption can be justified by the fact that the interaction between the nuclear spins is weak and higher order correlations can be neglected for a large number of nuclei.

Although the charge detection process in the experimental EDSR observations is in principle sensitive to the spin-flip probability, *P(t)*, in reality, the charge detection requires an integration over a large number of electric-field bursts and thus, the measured signal, *W(t)*, contains information about *P(t)* averaged over many pulses. The averaging process covers timescales exceeding the nuclear-spin diffusion time. *W(t)* therefore represents an average of all possible nuclear-spin configurations. In the theoretical description, this corresponds to a Gaussian integration over the longitudinal and

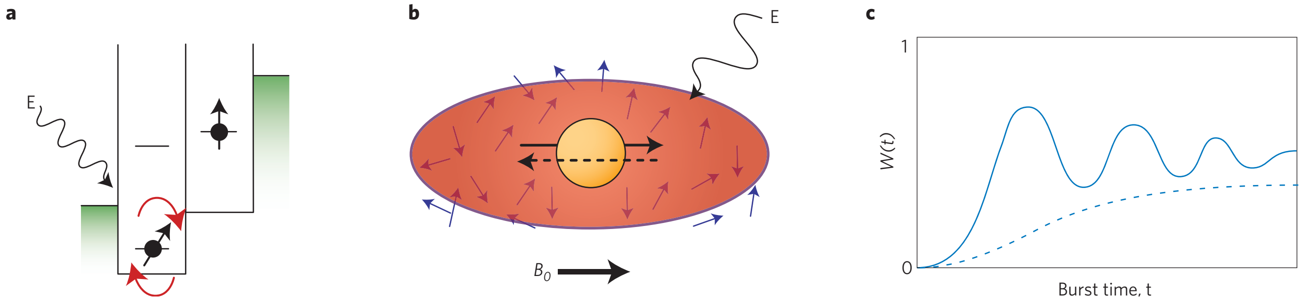

Figure 1 | Electrically manipulating spins in quantum dots. **a,** Band diagram of the experimental quantum dot system. An applied oscillating electric field induces spin-flips via EDSR, which manifest as oscillations in the transport characteristics owing to the spin-blockade phenomenon. **b,** A localized electron spin interacts with a nuclear spin bath, leading to decoherence. **c,** Time evolution of the probability W(t) of the dot's electron spin being in the 'up' state when the mediating mechanism is due to SO/inhomogeneous magnetic field (solid line) or a gradient of the Overhauser field (dashed line).

transverse components of the nuclear spins' magnetization with respect to the externally applied static magnetic field.

The details of the averaging process turn out to have direct consequences for experimental observations. For example, analytical formulas for $W(t)$ in the asymptotic limit for the SO coupling and magnetic-field-gradient mediated EDSR scenarios show oscillatory behaviour[4], a manifestation of Rabi oscillations observed in experiments[1,5]. More importantly, the theory shows that $W(t)$ is damped at a rate inversely proportional to the square-root of the burst time, t, with a universal phase shift with respect to the expected sinusoidal squared oscillation (solid line in Fig. 1c). This characteristic damping behaviour has also been observed experimentally[5]. Its origin is explained by the theory in terms of 'decoherence' owing to fluctuations in only the longitudinal component of the nuclear spins' magnetization.

In contrast, for the case of an Overhauser-field-mediated interaction between the electron spin and an applied electric field, fluctuations in both the longitudinal and the transverse components of the nuclear spin magnetization are important. As a characteristic signature differentiating it from the SO and magnetic cases, $W(t)$ was theoretically shown to have a monotonic increase with burst time (dashed line in Fig. 1c.) in agreement with the experimental observations by Laird *et al.*[3].

The presented mean-field theoretical approach seems to explain the experimentally observed EDSR transport characteristics in $W(t)$ very well. However, there are still challenges that remain to be addressed. One important aspect relates to the quantum nature of the nuclear spins, which was not considered fully in the presented theoretical framework, but would become important for large external magnetic fields[6]. In order to clarify the importance of hyperfine interactions with the nuclear spins on the electron spins' coherence, further experimental and theoretical studies are needed. Theoretical analyses along these lines would be challenging because the hyperfine coupling strength is not uniform over the nuclear spins involved (about 10^5–10^6) owing to the localized nature of electron wave functions. There seem to be at least two ways to avoid decoherence due to the nuclear spins. One is to manipulate the nuclear spin magnetization and to reduce its fluctuations by a controlled interaction with electron spins[7,8]. The dynamics in such a composite system would be an exciting field of future research. The other possible, but technologically challenging, avenue is to switch to other systems, such as *p*-type GaAs, Si/Ge or carbon nanotubes, which have much weaker interaction strengths with the nuclear spins[9]. ❐

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CONDENSED MATTER

How do your crystals grow?

More than 100 years ago, Wilhelm Ostwald predicted that crystalline structures would grow from the melt via a series of unstable states — now this cascade has been observed directly in an inorganic semiconductor.

Simon J. L. Billinge

Crystals nucleate out of molten material and then grow to make the beautiful, perfect, final product. How this happens is surprisingly complex and difficult to understand despite being studied for centuries. On page 68 of this issue[1], Chung and colleagues show for the first time the formation of a single crystallite through a cascade of intermediate forms on the way to the final thermodynamically stable state — an observation that supports Ostwald's 'rule of stages'.

Below the freezing-temperature, groups of atoms spontaneously congregate and separate from the melt, rather like clusters