previous works had sufficient detail or strength to make the quantum-gravity community pay attention, and consequently this possibility had been largely ignored.

In their paper in this issue, Jacob and Piran[1] have at last produced a comprehensive quantitative analysis. They show that, by comparing the arrival times of neutrinos with those of photons — as could be measured, for example, at the IceCube[9] neutrino telescope currently under construction in the Antarctic ice (Fig. 1) — all of the relevant numbers (including the expected rates of observation of neutrinos from gamma-ray bursts) conspire to provide a truly wonderful opportunity to improve the limits on η_1, and even to start exploring values of η_2 that are within the range of interest for the quantum-gravity problem.

On the basis of this analysis, it seems likely that neutrino telescopes will gradually take centre stage in quantum-gravity phenomenology. But, in closing, I also think it appropriate to stress the significance of these neutrino studies outside the peculiar context of quantum gravity. Given the tiny neutrino rest mass, the high-energy neutrinos picked up by telescopes such as IceCube are likely to be the most highly boosted particles we can observe. Even without the quantum-gravity motivation, the Lorentz sector of the Poincaré symmetries — so central to our present description of the laws of nature — deserves to be tested to the best of our abilities. Using neutrino telescopes, we will truly be accessing a new regime, and surprises wouldn't actually be so surprising.

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QUANTUM MEASUREMENT

A single spin made visible

In 1845, Faraday noted that the plane of polarization of light is rotated when a light beam travels through a material in a magnetic field. Now, Faraday rotation due to one single electron spin has been observed.

Lieven M. K. Vandersypen
is at the Kavli Institute of Nanoscience, TU Delft, 2600 GA Delft, The Netherlands.
e-mail: l.m.k.vandersypen@tudelft.nl

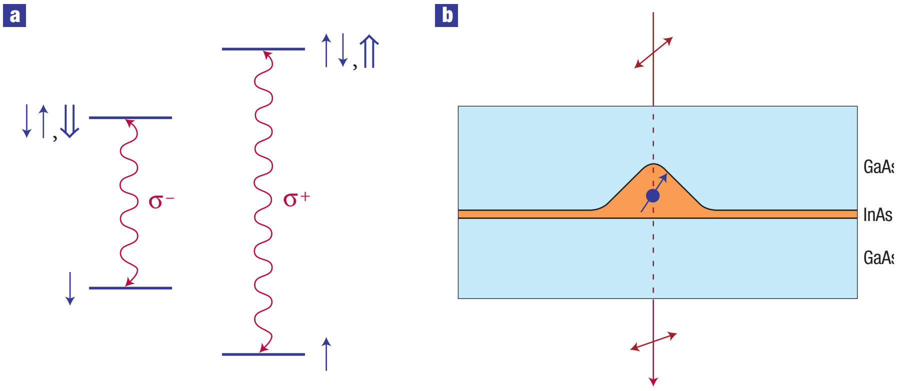

Figure 1 Faraday rotation due to a single spin. **a**, Level diagram showing the relevant allowed transitions between single-electron states and trion states. **b**, Schematic of the Faraday effect in a quantum dot device. The light polarization is rotated clockwise or anticlockwise depending on the orientation of the electron spin in the quantum dot (shown as an orange triangle).

The ability to measure the state of individual quantum systems has been instrumental for the history and development of quantum mechanics. Today, this ability is seen as one of the cornerstones of future quantum-information technologies. Working towards tapping this potential, Atatüre and colleagues report on page 101 of this issue the optical detection of the time-averaged signal from a single electron spin confined in a semiconductor quantum dot[1], an important step towards single-shot read-out of distinct spins.

The quantum dot used by Atatüre *et al.*[1] is a nanoscale self-assembled InAs island embedded in a GaAs substrate. A small number of electrons and holes can be trapped on the island, and the number is tunable by using a gate voltage. In the experiment of Atatüre *et al.*[1], the dot is initially occupied by a single electron, the electron's spin is continuously reinitialized by a pump laser to either spin-up (↑) or spin-down (↓), and this spin state was detected using a probe laser.

The probe laser would create bound electron–hole pairs (excitons) if the dot were empty. With one electron already present on the dot, a so-called trion is formed instead, composed of two electrons (in a so-called singlet state, here represented as ↑↓; see Fig. 1) and one hole. The relevant hole states have angular momentum 3/2 or –3/2 — which we denote ⇑ and ⇓ — along the growth direction of the GaAs/InAs structure. Optical selection rules allow only two transitions between single electron states and trion states: right-handed circularly polarized light, σ^+, excites the transition between ↑ and {↑↓,⇑}, and left-handed circularly polarized light, σ^-, couples ↓ and {↑↓,⇓} (see Fig. 1).

A straightforward approach to optical read-out of the spin state would consist

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of resonant fluorescence or resonant absorption of circularly polarized light. Such state-dependent fluorescence or absorption measurements have been used to read out the spin state of a single trapped ion[2], a single molecule[3,4] or a single nitrogen-vacancy centre in diamond[5]. In semiconductor quantum dots, however, this approach cannot be used, mainly because too much of the light scatters in the substrate in which the dot is embedded.

Atatüre *et al.*[1] circumvent this problem by using off-resonance dispersive detection[6]. With the probe laser detuned far from resonance, the presence of the optical transition merely induces a phase shift in either the σ^+ or σ^- component of the transmitted light, depending on whether the electron on the quantum dot is ↑ or ↓. As a result, the polarization of linearly polarized light — which can be viewed as a superposition of σ^+ and σ^- light — will be rotated clockwise or anticlockwise depending on the electron spin state. This effect, known as the Faraday effect, has been widely used to probe the polarization of large ensembles of spins in semiconductors[7]. As elegantly shown by Atatüre *et al.*[1], even the signal from a single semiconductor spin is detectable with this method.

In the present experiment[1], the Faraday rotation amounted to only about 10 μrad, and for the weak laser powers used, the signal had to be averaged for about 100 ms in order to obtain a signal-to-noise ratio of unity. By that time, the spin state may well have been flipped due to interactions with its environment. Furthermore, the probe laser light scattering off the spin can flip the spin as well (in addition to causing an unavoidable quantum-mechanical back-action that 'collapses' superposition states into either ↑ or ↓ on measurement). In practice, the spin state would be changed multiple times while it is being measured. In the Atatüre experiment[1], it was therefore necessary to continuously reset the spin to the same state using a pump laser during the measurement, so that a net spin signal could be collected.

In the future, such averaging may not be necessary: the authors estimate that with technical improvements, it should be possible to reduce the measurement time and at the same time largely eliminate measurement-induced spin flips. Embedding the quantum dot in a cavity can further enhance the signal, as the rotation of the light polarization accumulates when the light bounces back and forth in the cavity. This was demonstrated in a recent experiment by Berezovksy *et al.*[8] that is similar in spirit to the work of Atatüre and colleagues[1]. These advances can lead the way to true single-shot read-out of the spin state of a single electron in a quantum dot by optical means, without requiring any averaging over an ensemble or in time. Such single-shot read-out is essential for quantum-information processing based on spins in quantum dots, but has so far only been realized using electrical detection[9].

Furthermore, the dispersive method can in principle be non-destructive, and would thus allow for quantum non-demolition measurements of the spin state. A quantum non-demolition measurement preserves the eigenstates of the system hamiltonian, so that repeated or continuous measurements are possible and meaningful[10]. It is a very general concept that has been applied first in quantum optics and atomic physics, but now also makes its way into solid-state qubit systems, for instance — as reported elsewhere in this issue[11] — for qubits based on Josephson junctions.

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QUANTUM DOTS

Collective radiance

Evidence for the superradiant behaviour of quantum dots — behaviour first described in the context of atoms in a gas over 50 years ago — suggests they can radiatively interact over distances of at least 150 nm.

Galina Khitrova and Hyatt M. Gibbs
are in the College of Optical Sciences, University of Arizona, Tucson, Arizona 85721, USA.
e-mail: khitrova@att.net

Demagogues, orchestra conductors, and physicists all know that a system's collective behaviour can be greater than the sum of its parts. In optics, the groundwork for exploiting such behaviour was begun by Robert Dicke[1], who considered an ensemble of gas atoms as a single quantum-mechanical system, and showed that the radiative coupling between atoms, even if only one of them is excited, can significantly alter the rate at which they radiate. Moreover, he expected that this behaviour would be most pronounced for systems whose atoms were essentially indistinguishable and contained within a volume smaller than a wavelength of the emitted light. Under the correct conditions then, a gas could be made to spontaneously emit light in a time shorter than its constituent atoms in isolation — one form of a general phenomenon known as superradiance. Over half a century later, Scheibner and colleagues[2], on page 106 of this issue, identify the signatures of superradiant behaviour by an ensemble of quantum dots — perhaps the beginning of radiatively mediated cooperativity between dots.

The simplest system in which such radiative cooperation can be understood is that of two identical atoms separated by a distance smaller than the wavelength of emitted light, but longer than that for which the dipole–dipole interaction destroys cooperation. Such a system has two possible eigenstates — a subradiant (or 'dark') state that does not radiate, and a superradiant state that radiates twice as fast as either of its atoms in isolation. As a result, the emission dynamics of the system will depend on how it is excited[1].

A system somewhat more complex than two atoms — and one that can be realized in the solid state — consists of

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