QUANTUM DOTS

Driven to perfection

In many ways, semiconductor quantum dots behave like natural atoms, but it has proved difficult to manipulate them using resonant laser light. That problem is now overcome.

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At low enough temperatures, quantum dots in semiconductors can have sharp optical transitions, similar to those of atoms. In recent years there has been intense interest in demonstrating various coherent optical control techniques in these 'artificial atoms' for applications in quantum communication, quantum computation and nonlinear optics at low light levels. But a number of experiments that are standard in atomic physics have remained elusive for quantum dot systems. One of the main problems has been that the structures used to isolate the dots typically scatter a lot of light, so it is difficult to excite on resonance and collect fluorescence at nearly the same wavelength. In the past this has led most researchers to work with non-resonant excitation schemes involving higher excited states, but these are very short-lived, and lose coherence quickly. Nevertheless, considerable progress has been made recently in resonant optical control using techniques such as 'differential transmission'[1] or connecting two different optical transitions by single broadband pulses[2].

Reporting on pages 198 and 203 of this issue, two independent studies by Nick Vamivakas and colleagues[3] and Edward Flagg and colleagues[4] demonstrate how to fully overcome the difficulty of exciting and collecting at the same wavelength. Using neutral[4] and charged[3] single quantum dots, the two groups have demonstrated direct detection of resonance fluorescence signals under intense optical excitation, as well as measurement of the second-order photon statistics of these signals. More specifically, a two-level atomic transition excited on resonance by an intense optical field is expected to produce a distinctive three-peaked fluorescence spectrum, as was first shown theoretically by Mollow[5] and subsequently observed in sodium atoms[6]. This behaviour is most easily understood in a so-called dressed-state picture (see Fig. 1). Four optical transitions are allowed between two energy-level manifolds having N or $(N-1)$ total photons and atomic excitations. As two of these transitions are degenerate, the spectral signature consists of three lines, known as the 'Mollow triplet'. The Mollow triplet was recently observed in single molecules[7], but has, until now, never been demonstrated in semiconductor quantum dots.

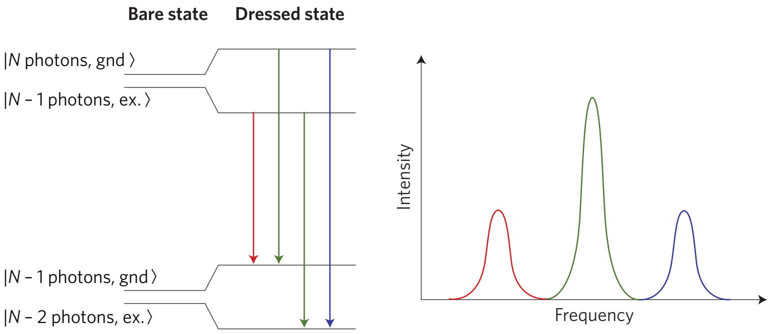

Figure 1 | The Mollow triplet. The quantum state of an atom or a quantum dot coupled to an intense optical field can be best described in the 'dressed-state picture'. The bare state is characterized by a photon number and the state of the atom, which can be either in its ground (gnd) or in its excited (ex.)state. Four optical transitions are possible between the dressed states where the total number of photons plus atomic excitations is N, and the manifold where it is $(N-1)$. These transitions give rise to the 'Mollow triplet'.

Flagg *et al.*[4] studied resonance fluorescence measured from neutral quantum dots coupled to a planar microcavity. By exciting the dots from the side, using guided modes of the cavity (and thus confining the light between the mirrors of the cavity), they greatly suppressed scattering, and in this way obtained fluorescence signals from single dots that were nearly free of unwanted laser scatter. An important result is that the linewidths of the fluorescence signal do not seem to broaden significantly at higher excitation powers. This cannot be assumed *a priori* in quantum dots, given that the picture that they behave like single atoms is only an approximation. One of the key results of this work is a set of photon-correlation measurements that show the expected oscillatory behaviour, which is a signature of coherent Rabi oscillation in the time domain.

The work of Vamivakas *et al.*[3], on the other hand, takes resonance fluorescence measurements in a new direction. They explore the method as a means for measuring electron spin in charged quantum dots. Their devices include electrical gates that allow a single electron to be controllably loaded into a dot. The experimental geometry that they used produced more unwanted laser scatter than in the experiments of Flagg *et al.*[4], but through spectral and polarization filtering they managed to observe the outer peaks of the Mollow triplet with little background. For electron-spin measurement, a magnetic field parallel to the growth direction of the quantum dot (known as the 'Faraday geometry') was used to lift the degeneracy of the optical transitions corresponding to the spin-up and spin-down states. The optical detuning (that is, the difference between the frequencies of the excitation laser and the transition) is then different for each spin state, and as a result the positions of the outer peaks of the Mollow triplet depend on the spin state. The experiments reported by Vamivakas and colleagues[3] confirm that reasonably well-separated fluorescence sidebands can be observed corresponding to spin ±1/2. The advantage of this kind of measurement is that many photons can be emitted without altering the spin state; a similar approach has already been used for high-fidelity readout in other systems, such as trapped ions. A single-shot spin measurement — without the need for averaging over several measurements — was not demonstrated as part of this work, but it seems to be within reach.

Taken together, these results[3,4] seem to open many new possibilities with quantum dots. From a technical viewpoint, any optical control or detection scheme that is possible in atoms is now feasible for quantum dots, even those involving resonant excitation and collection of photons scattered at the same wavelength, or excitation powers far in excess of the saturation power. Some interesting problems remain, however. For example, is there any way to obtain in the same quantum dot both a 'cycling transition' (which Vamivakas *et al.*[3] demonstrated to be optimal for readout), and 'Λ-type transitions'[2], which are good for optical spin manipulation and the conversion of information stored in the stationary quantum-dot qubit to 'flying' photonic qubits? In any case, we expect to see rapid progress over the next few years in areas such as single-shot readout and stationary-to-flying-qubit conversion that will realize the promise of quantum dots as a system that is suitable for quantum-information applications and yet fully integrable into a microphotonic network. ❐

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NUCLEAR MAGNETIC RESONANCE

The benefits of travel

Nuclear magnetic resonance (NMR) is widely exploited for imaging, particularly in medicine. Writing in *Nature*, David Brunner and colleagues propose a subtle change to the NMR technique that could improve both the clarity of the images produced and the experience of a human patient during imaging (*Nature* **457,** 994–998; 2009).

Traditionally in NMR imaging a standing radio-frequency wave is created within the sample under study, causing the atoms' nuclear magnetization to 'wobble' (or nutate); the subsequent precession of the magnetization is then picked up by a probe and processed into images. Brunner *et al.*, however, have found advantages to using a travelling, rather than a standing, radio-frequency wave.

The motivation comes from the electrodynamics of the situation: the magnetic field must exhibit curvature, and for a standing wave that means spatial variation in the magnitude of the field; for a travelling wave, however, the curvature can instead be accommodated in phase variation, which means that the magnitude of the field is more uniform, and therefore better for imaging.

Using a travelling wave also means that the NMR probe must be configured differently. In the standing-wave case, the probe (and hence any potentially hazardous, strong electric field emanating from it) is positioned very close to the sample, or patient.

For travelling-wave NMR, however, the probe can instead be moved some distance away, because it couples to the propagating modes of the waveguide formed by the body of the scanner. This improves the performance of the probe, but it also frees up more space inside the scanner for the patient — claustrophobia can often be a problem for patients undergoing scans.

In the lower-leg scans shown here, produced by Brunner *et al.*, the benefit of imaging using a travelling wave (left) is clear, compared with the conventional approach (right). There are challenges to extending the travelling-wave technique to whole-body imaging — notably diffraction and attenuation at dielectric interfaces such as the shoulders. But the authors suggest that wave impedance matching (which they have already been able to demonstrate using bottles of mineral oil as imaging samples) should be an effective method for counteracting such effects.

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