QUANTUM DOTS

To the source of the noise

Distinguishing between different sources of noise in quantum dots could help to develop single-photon devices that are suitable for long-range entanglement.

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The peculiar laws of quantum mechanics offer fundamentally new paradigms for information processing. Ultra-secure quantum communication systems are already commercially available, and researchers now aim to devise the quantum information processors that could provide an exponential speed-up of certain computational problems. Several different physical systems could potentially realize these visions. Among them, semiconductor-based approaches are attractive because they build on the technology that is already used for present-day electronic circuits. Furthermore, they provide an interface between solid-state quantum systems and quantum optics, which is useful for long-range transfer of quantum information.

However, a challenge associated with all solid-state systems is that they tend to be inherently noisy, which degrades quantum information by causing decoherence. Writing in *Nature Physics*, Andreas Kuhlmann and his co-workers now present a systematic study of two different noise sources in self-assembled semiconductor quantum dots[1]. By comparing noise measurements at slightly different photon energies, they are able to disentangle the contributions from nuclear spins and charge fluctuations — the two dominant sources of noise in this and several other systems. Furthermore, they show that by measuring quickly enough, one can generate optical emission from the dots with a spectral broadness that is limited by the lifetime of the underlying quantum states rather than extrinsic noise sources. Reaching this limit is an important step towards creating indistinguishable photons from different sources, which in turn enables long-range entanglement.

The quantum dots used in the study were nanometre-sized islands of indium arsenide embedded in gallium arsenide. They are called self-assembled because these islands emerge spontaneously under appropriate growth conditions due to an atomic lattice mismatch of the two materials. As a result of the lower band gap of indium arsenide, the quantum dots trap both electrons and holes. Thus, they can also confine excitons — bound pairs of electrons and holes. Owing to this confinement, the excitons have discrete quantum states that lasers can address individually. The decay of an exciton through electron–hole recombination leads to the emission of a single photon whose wavelength is determined by the exciton energy. Using polarised light, one also has direct access to the spin degree of freedom.

To exploit quantum effects in optics, it is often essential that photons emitted from different sources are able to interfere, which means that they must have the same wavelength. However, the emission energy usually fluctuates as a result of various noise sources in the semiconductor, which limits the visibility and fidelity of interference effects. Another reason to strive for a low-noise environment is that quantum superposition states — which are a key requirement for quantum-enabled technologies — rapidly lose their phase coherence and thus their quantum nature when subjected to noise.

The two dominant noise sources in the quantum dots studied by Kuhlmann and colleagues are fluctuating nuclear spins and electrical noise that presumably arises from background charges. The importance of nuclear spins is well known and their interaction with electrons, excitons and holes has been studied in considerable detail[2,3]. A self-assembled quantum dot typically contains about 10^4 nuclei. Electrons and holes experience a randomly fluctuating effective magnetic field, and thus Zeeman splitting, caused by these nuclear spins. Taming the fluctuations is of great practical importance, and understanding the dynamics of a single electron or hole spin coupled to a mesoscopic ensemble of nuclear spins, the so-called central spin problem, is also of fundamental interest. Charge fluctuations, on the other hand, typically arise from electrons hopping into, out of or between trapping sites, and have been studied more sporadically. They affect exciton states through the Stark effect and can also couple to spin states — by modulating the exchange interaction or through spin–orbit coupling, for example. It is rather difficult, however, to obtain a universal understanding of these effects because charge traps can occur at many different sites and depend sensitively on the growth process.

Kuhlmann *et al.* demonstrate a method to distinguish charge and nuclear spin fluctuations[1]. They measure the resonant

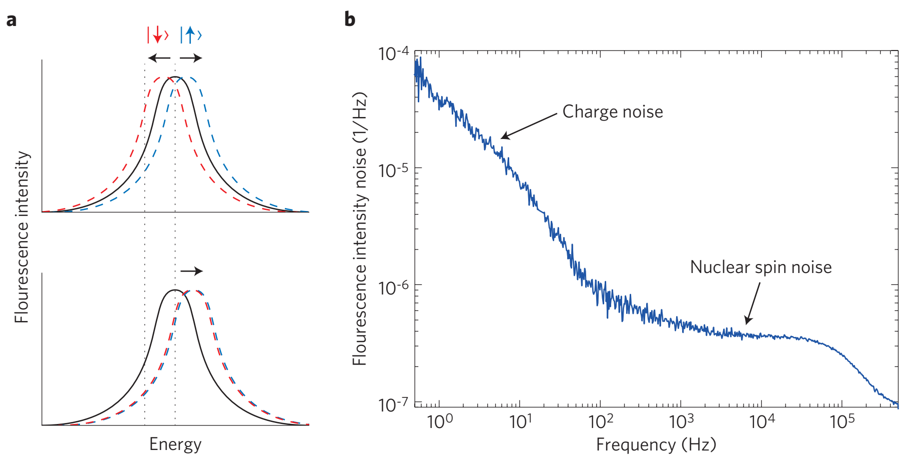

Figure 1 | The effect of noise on the resonance fluorescence spectrum. **a**, Spin fluctuations shift the quantum-dot emission line in opposite directions for different exciton spin states (top), whereas charge fluctuations affect both in the same way (bottom). The two contributions can be distinguished by measuring on and slightly off resonance (vertical dotted lines). **b**, The two Lorentzian-like features can be identified as charge and spin fluctuations in a typical noise spectrum. Panel **b** reproduced with permission from ref. 1, © 2013 NPG.

fluorescence of exciton transitions in a quantum dot illuminated by a laser, and make use of the fact that charge and spin noise affect the resonance differently (Fig. 1a). Charge noise couples to both spin states of the exciton in the same way, thus shifting the complete fluorescence spectrum. Nuclear spin fluctuations on the other hand shift the energy of the two spin states in opposite directions. When the laser is slightly detuned from resonance with the quantum-dot exciton, the effect of spin noise on the fluorescence intensity thus partially cancels out — as one contribution increases, the other decreases. In contrast, the maximum height of the resonance is most sensitive to spin noise. By acquiring a noise spectrum of the fluorescence intensity at both detunings, one can thus tell which features in the noise spectrum arise from which source (Fig. 1b). Interestingly, the authors find that the nuclear spin noise extends to much higher frequencies than the charge noise. They quantitatively reproduce their result with a model that includes both noise contributions and their nonlinear effect on the fluorescence intensity. In addition, they show that by measuring a resonance spectrum quickly enough, the broadening can be eliminated entirely if the fluctuations are slower than the sweep rate and thus just shift rather than broaden each individual spectrum.

There are two aspects of these experiments that are particularly noteworthy. First, the team directly probed the fluctuations seen by a self-assembled quantum dot in the time domain and on the relevant timescales, which has rarely been done in the past. It is likely that the results will motivate further work aimed at obtaining a complete understanding of the dynamics and the associated dephasing of electron spin states. A potential difficulty in this respect may lie in the apparent speed-up of the dynamics due to the laser illumination. Second, the results identify the importance and magnitude of charge noise. Kuhlmann *et al*. show that, similar to many semiconductor quantum devices, reducing decoherence owing to charge noise is key for improving device performance, and hence methods to characterize it are of great interest. The nonlinearity of the present measurement scheme may turn out to be an inconvenience as it makes it difficult to directly extract noise spectra of the individual contribution without resorting to a model, but this limitation could probably be overcome with further refinements. ❒

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Published online: 28 July 2013