QUANTUM TOMOGRAPHY

Measured measurement

A method for characterizing quantum measurement devices completes the suite of 'tomography techniques', which should enable us to learn all there is to know about a given quantum-physics experiment.

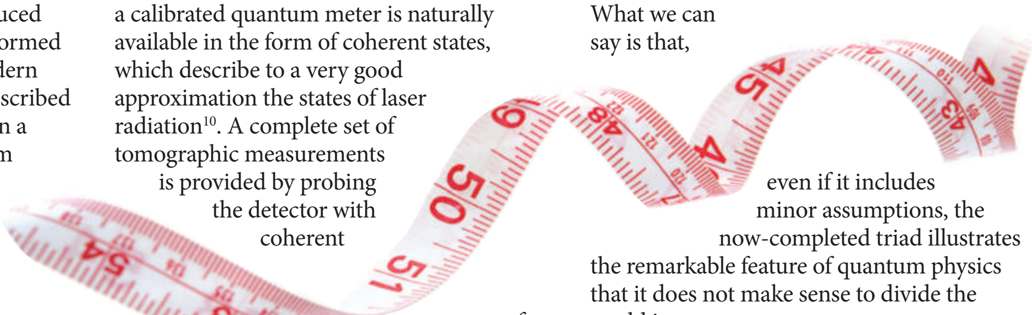
Markus Aspelmeyer

A typical day in the quantum-optics lab course: two gifted and enthusiastic third-year students have just proved quantum theory to be wrong. Its predictions do not match the experimental observation. When repeated measurements confirm the results, one of the two already starts developing faint hopes for a Nobel Prize — until an instructor enters the scene and explains to the students where their measurement had gone wrong. One of the wave plates involved in the measurement of photon polarization was labelled incorrectly by a previous user. Quantum theory has been saved, once again. But still, the experience highlights a general problem: how can we be sure that a certain measurement device used in the laboratory 'behaves' according to our expectations? Or, to put it the other way around, given a real measurement device, how do we best describe its effect in the framework of quantum theory? Jeff Lundeen and colleagues[1] now provide an experimental solution to answer this question: by measuring the measurement apparatus.

In quantum physics, each experiment resembles a specific 'observational situation'[2], in which the wavefunction of the experiment contains the probabilities of all possible outcomes for all possible measurements. A complete description of a given quantum-physics experiment therefore boils down to knowing its wavefunction, which typically comprises knowledge about the produced state, its dynamics and about the performed measurement. In the language of modern quantum theory, this knowledge is described by (positive semidefinite) operators on a Hilbert space. Every working quantum physicist is then left with the question: which operators best represent the system and measurement at hand? The system side has been covered by quantum-state tomography[3,4]. There, a sequence of calibrated measurements on identically prepared states enables the reconstruction of the full density matrix (which provides complete knowledge of the quantum system). Using maximum-likelihood estimation methods eventually recovers the operator that comes closest to the experimental observations[5,6]. Recently, this procedure has also been used to quantify the dynamics of a quantum state via quantum process tomography[7–9], which has become a powerful analysis tool for quantum-information processing. The calculation of experimental expectation values, however, requires an accurate knowledge of the detector used for the tomography measurements.

To realize quantum-detector tomography, Lundeen *et al.* have been turning the tables. Instead of performing calibrated measurements on identically prepared quantum systems, they use a well-calibrated quantum system as a meter for measuring the measurement apparatus. The idea is the same as above: as experimental outcomes are determined by both the system and the measurement device, accurate knowledge of the system can be used to reconstruct the density matrix of the measurement apparatus that best describes the experimentally observed values. To accommodate experimental imperfections (that could lead to a non-physical reconstructed density matrix), they make use of so-called convex optimization to find the optimal physical representation of the unknown detector.

Their experiment is geared towards characterizing single-photon detectors, one of the core ingredients in modern quantum-optics and photon-based quantum-information experiments. For these detectors, a calibrated quantum meter is naturally available in the form of coherent states, which describe to a very good approximation the states of laser radiation[10]. A complete set of tomographic measurements is provided by probing the detector with coherent states of different amplitudes.



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Lundeen *et al.*[1] compare two types of detectors: a commercial avalanche photodiode that is sensitive to single photons but cannot tell how many photons participate in a detection event, and a home-made single-photon detector that can resolve the number of detected photons. Their experimental reconstruction reveals the striking difference between the measurement operators that need to be used to correctly describe these two systems. But it also provides a direct quantitative comparison between the two. This is a particularly relevant feature as measurement procedures are becoming increasingly important in the context of quantum metrology and quantum-information processing. One could even envisage a calibrated measurement apparatus that is optimized to a specifically tailored quantum circuit. From a purely practical point of view, the detector tomography demonstrated by Lundeen *et al.* provides a direct operational approach to comparing and calibrating the performance of different photon detectors — without the need for a specific model of the apparatus.

Finally, the advent of quantum-detector tomography also raises an interesting philosophical question. Does the completion of the 'triad' of state, process and detector tomography mean that we can indeed fully specify, from a quantum-theory perspective, an experiment without any additional assumptions? It is hard to avoid being caught in a circular argument; state tomography requires perfect knowledge about the detector, and process and detector tomography rely on exact knowledge of the state — a real chicken-or-egg dilemma. What we can say is that, even if it includes minor assumptions, the now-completed triad illustrates the remarkable feature of quantum physics that it does not make sense to divide the world into quantum states, quantum processes and quantum detectors. Once we have decided on the experiment — that is, once the apparatus is set up — we can obtain a full description of its overall wavefunction and hence on the probabilities of all possible outcomes. And it is completely up to us what to call state, process or detection in 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. ❐

Markus Aspelmeyer is at the Institute for Quantum Optics and Quantum Information, Austrian Academy of Sciences, Boltzmanngasse 3, A-1090 Vienna, Austria.
e-mail: markus.aspelmeyer@quantum.at

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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