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QUANTUM OPTICS

Single-atom transistor for light

Scott Parkins

A subtle quantum-interference effect has been used to control the optical response of a single atom confined in a cavity. It could offer a means to develop logic gates for an optical quantum computer.

In a nonlinear optical medium, the electric polarization induced by an incident light beam (or beams) exhibits a nonlinear dependence on the light's electric field. This nonlinearity, which can give rise to optical effects such as harmonic generation, or an intensity-dependent refractive index (the optical Kerr effect), is typically very small and limited in usefulness by absorption of the beam when the frequency of light is too close to an atomic resonance in the medium. Consequently, nonlinear optical effects are generally associated with bulk media and high-intensity light fields far from resonance with atomic transitions. However, in recent years, there has been a significant trend in experimental quantum optics towards nonlinear optical effects at progressively lower intensity levels, with the ultimate goal being the realization of large interactions and conditional dynamics between light fields at the level of individual light quanta — that is, between single photons. This would enable the operation of quantum logic gates with single photons — the building blocks of an optical quantum computer.

Spurred on in large part by this possibility, researchers have been striving to realize nonlinear optical systems that can operate at the single-photon level with minimal losses or 'decoherence', and with media that can themselves be coherently controlled and manipulated at the quantum level. On page 755 of this issue, Mücke and colleagues[1] report an experiment that takes an important step in this direction by applying the elegant technique of electromagnetically induced transparency to a single rubidium atom inside a microscopic optical cavity.

Microscopic optical cavities such as that used by these researchers — a pair of closely spaced, highly reflective mirrors — can confine light fields with specific wavelengths in a small region of space and greatly enhance the 'electric field per photon' at those wavelengths. If the mirror spacing is carefully tuned to the wavelength of a transition between two electronic states of an atom confined in the cavity, then it is possible to achieve a strong resonant coupling between the atom and a single photon in the field. In fact, the strength of this coupling, which gives the rate at which the field and atom exchange a quantum of energy, may be so large as to exceed energy decay rates in the system caused by the small but finite transmission of the mirrors and atomic spontaneous emission. This corresponds to the strong coupling regime of cavity quantum electrodynamics, whereby coherent quantum dynamics is dominant and enables a multitude of possibilities for preparation, manipulation and measurement of quantum states[2]. Furthermore, optical cavities, with their well-defined spatial modes and input–output channels (through the mirrors), provide an efficient interface between propagating light fields and matter in the form of one, a few or many atoms[3].

Electromagnetically induced transparency (EIT) uses destructive quantum interference between two alternative routes from a ground to an excited atomic state to eliminate absorption of light (and hence losses) associated with this atomic transition. In alkali atoms such as rubidium, which was used in the authors' experiment[1], EIT can be implemented with transitions from two hyperfine ground states to a single excited state: one driven by a control laser field, which 'dresses' the excited state and determines the optical response of the medium to another, weaker probe field, which drives the other transition. The occurrence of EIT corresponds to the preparation of a 'dark atomic state' — a non-absorbing coherent superposition of the two ground states. Significantly, however, this elimination of absorption can occur even for light fields close to, or at resonance with, the atomic transition, a regime in which the nonlinear response is maximized and in which giant optical nonlinearities can be realized[4,5]. A spectacular demonstration of this capability was provided in 1999 by an experiment[6] with a sodium Bose–Einstein condensate (a sample of ultracold atoms all in the same quantum state). This work generated a Kerr nonlinearity almost seven orders of magnitude larger than had previously been achieved with cold atomic gases, enabling the

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50 & 100 YEARS AGO

50 YEARS AGO

'Self-regulation for children' — In the review of our book "The Free Family" ... Prof. Vernon says that "it is clear that the children experienced considerable difficulty in adapting themselves to the society of children very differently brought up", and he asks for independent evidence for their "spontaneity, poise and stability". Allow me to say that Prof. Vernon could only have gained the first false impression because we describe in detail the kind of conflicts one of our children had in a specific instance. This certainly does not imply that our children had more difficulties in 'socialization' than other children. This is particularly true for the second, third, fourth and fifth child. All their school reports have tended to stress their ability to co-operate ... We started self-regulating children when I was a student on a very meagre grant and I have always had little inclination for leisure. Flexibility we have had, more so than the normal parents, and it is useful; but money and leisure are not important criteria.

From *Nature* 11 June 1960.

100 YEARS AGO

The investigation of the microstructure of hailstones in summer having proved very difficult, if not impossible, I constructed an apparatus ... for their preservation until winter time. The apparatus consists of three co-axial cylinders; the inner space is intended for hail; the middle space for a mixture of ice and cupric sulphate (approximately in the proportion corresponding to eutectics $t = -1.6°$); the outer space for ice, forming a sort of guard coat ... For the investigation of the microstructure of a separate hailstone Mr. W. Dudecki and I made a thin section of it by first rubbing one side on emery-paper or by melting it with the warmth of a finger. This side was laid upon an object-glass and frozen to it, after touching for some time with a finger the other side of the glass.

From *Nature* 9 June 1910.

speed of light in the medium to be reduced to just 17 metres per second.

Mücke and colleagues' study[1] now marries single-atom, strong-coupling cavity quantum electrodynamics with EIT. It brings low-loss, giant optical nonlinearities into the realm of both single photons and single atoms, and represents a milestone in the control of matter and light at the fundamental level. In their experiments, the authors trap one or a few rubidium atoms between two mirrors separated by half a millimetre, then monitor the transmission of a weak probe laser through the cavity — so weak, in fact, that on average the photon number inside the cavity is much less than one.

The key indicator for EIT is the contrast between transmission around the atomic resonance with and without application of the control laser field. The authors' observation[1] of a 20% contrast with just one atom provides a clear demonstration of entry into the above-mentioned realm, and readily achievable increases in the atom–cavity coupling strength should push the contrast well above 90%. This would enable operation of the single-atom system as a near-ideal transistor, controlling coherently the passage of light through the cavity. In fact, such increases would also make possible a Kerr-effect-induced 'photon blockade' mechanism, whereby excitation of the atom–cavity system by a single probe photon actually prevents further excitation by subsequent probe photons.

Besides its obvious relevance to conditional quantum dynamics and quantum-information processing, this mechanism is also central to recent fascinating proposals for strongly interacting photon gases and many-body phenomena (for example, quantum-phase transitions) in arrays of coupled cavities[7]. It would also enable EIT-based coherent transfer of quantum states between light and matter, in which a time-dependent control field leads to the 'mapping' of photons from an incident field onto cavity-confined atoms or vice versa[4], opening the door to a plethora of unique possibilities for quantum-state generation and manipulation. ■

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NEUROSCIENCE

fMRI under the spotlight

David A. Leopold

Analysis of a selected class of neuron in the brains of live animals using functional magnetic resonance imaging (fMRI) opens the door to mapping genetically specified neural circuits.

Advances in modern brain research are such that the line between science and science fiction can sometimes seem blurred. During the past 20 years, two advances have redefined the limits of experimental neuroscience. The first is functional magnetic resonance imaging (fMRI), which is widely used to map brain activity in humans. The second is genetic reprogramming of brain cells using molecular genetics. In an elegant study on page 788 of this issue, Lee *et al.*[1] combine these methods to demonstrate that, in the rat brain, the direct activation with light of a genetically defined subclass of neuron leads to robust fMRI responses. This finding not only demonstrates a tight link between neural firing and fMRI responses, but also introduces a powerful tool for mapping the function and dysfunction of large-scale brain circuits.

Functional MRI has had an enormous impact on modern science, with neuroscientists, psychologists, clinicians and even economists basing their conclusions on stunning images of brain activity obtained using this technique. But critics argue that, because fMRI measures changes in blood flow (haemodynamics) rather than information-carrying electrical signals within neurons, its results are often open to interpretation. Indeed, although it is tempting to explain positive fMRI signals as an increased rate of action-potential firing by neurons, this one-size-fits-all interpretation is unlikely to be correct. For instance, some electrophysiological experiments have shown that the simmering, sub-threshold activity of neurons is better correlated with haemodynamic fluctuations detected by fMRI than are action potentials[2]. Other evidence[3,4] suggests that the local coupling between action potentials and haemodynamic signals varies with behavioural context.

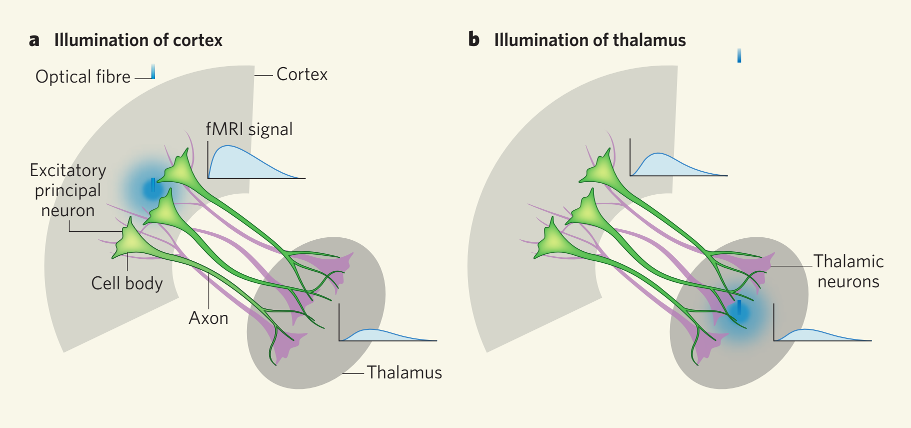

Figure 1 | fMRI responses to stimulations near and far. Lee *et al.*[1] genetically modified rat cortical neurons to produce light-sensitive membrane channels. They found that selective optical stimulation of cell bodies in the cortex (**a**) or axons in the thalamus (**b**) yield fMRI responses in both regions. The strongest and most immediate responses, however, were detected in the cortex in response to direct stimulation.

At the heart of the problem are the many complex cellular and molecular mechanisms that govern blood flow[5]. Lee *et al.*[1] therefore measured fMRI responses to the direct activation of a certain subtype of neuron, which they manipulated with optogenetics. For this, they used a viral vector to introduce two genes into rat brain cells called excitatory principal neurons. One of the genes encoded a fluorescent protein of glowing jellyfish origin[6], and so served as a marker to verify precisely which cells were manipulated. The other gene's product was channelrhodopsin, a light-sensitive, membrane-associated protein from a species of green alga[7]. By making a restricted class of cell sensitive to light in this way, the authors could selectively manipulate the activity of those cells while leaving other circuit elements unperturbed.

This group has previously used[8] such an approach to demonstrate moment-by-moment experimental control over a mouse's running behaviour — by illuminating neurons in an area of the motor cortex, the brain region responsible for voluntary movements. What makes the present study a technical tour de force is the researchers' measurement of haemodynamic and electrical responses to optogenetic stimulation in the brains of