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Quantum information

Atomic recorder for light quanta

Jean-Michel Raimond

The quantum information carried by a faint laser pulse has been trapped in a gas of atoms. This 'quantum memory' paves the way for networks that transmit and process information in non-classical ways.

Most of the information we get through the World Wide Web travels encoded on inch-long laser pulses rushing at light-speed down hair-thin glass fibres many thousands of leagues under the seas. One day, that information might be coded onto the quantum properties of these pulses, the weird rules of quantum logic opening a wealth of new possibilities[1]. Processing this information would require that it be copied from the light onto motionless objects, to be stored. But quantum states are fragile, and copying them is not easy. In a step towards the realization of a quantum-information network, Julsgaard *et al.*[2] demonstrate just such a quantum memory, in which the state of a faint laser pulse is faithfully copied onto an ensemble of atoms (see page 482 of this issue).

The power and strangeness of the quantum arise from a few striking properties. Quantum systems can be in a superposition of states, allowing quantum bits (qubits) to take two logical values at once. Quantum states cannot be cloned — a copy operation inevitably destroys the original. This is a key point for quantum cryptography[3], as an eavesdropper cannot access quantum information without revealing his presence. Quantum systems can be entangled, forming a single entity whatever the physical distance between them, and these weird correlations are used for teleportation[4] — a quantum 'fax machine' that transmits a quantum state independently of the particle that carries it.

Light quanta (photons) or faint laser pulses are excellent carriers of quantum information. They travel unaffected over long distances, are easily read out in detectors, and hence have been thoroughly exploited for quantum tests[5], cryptography[3,6] and teleportation[4,7]. For many purposes, however, their main quality — that they travel at the speed of light — is an inconvenience, as they cannot be stored for any extended time; the best optical resonators available so far can store photons for a few tens of microseconds only. It is thus rather difficult to process the quantum information that light carries in a quantum way. We need quantum memories.

One natural approach, when it comes to single photons, is to map them onto the state of a single atom, the interface being provided by a resonant cavity, for instance. Atom–photon information-exchange experiments have already been realized, but at the expense of using quite complex experimental techniques[8]. Moving to the many-photon case, mesoscopic light pulses can be 'stopped' in their tracks[9]: the light velocity is reduced to mere metres per second, even to zero, in an atomic medium that has an extraordinarily large index of refraction. The light field can then be mapped onto an atomic excitation and can be retrieved later (milliseconds later in real situations). But so far these experiments, although spectacular, have involved rather intense pulses of light, whose quantum properties are not apparent.

Julsgaard *et al.*[2] worked instead with light pulses made up of only a few photons, mapping their quantum properties onto those of an atomic ensemble. The experimental set-up is quite simple, based on glass cells holding atomic vapour of caesium at a temperature close to room temperature. For an efficient copy to be made, light and atoms must have the same quantum structure. In the special conditions used here, both are described by two continuous quantum variables, or observables — $\hat{X}_L$ and $\hat{P}_L$ for the laser, $\hat{X}_A$ and $\hat{P}_A$ for the atoms. Each pair is equivalent to the observable quantities position and momentum for the motion of a single particle. These are incompatible:

100 YEARS AGO

I have read with interest in your columns… a carefully compiled and instructive account of the discussions that have from time to time during the past 50 years broken out with regard to the naming of the highest measured point on the earth's surface, Peak XV of the Indian Survey. I have long maintained it to be a matter for regret that the monarch of mountains should be called after any individual, however eminent, and I am still of this opinion, which is shared by most mountaineers and mountain lovers. We should prefer that Peak XV should bear a Nepalese or a Tibetan name, even had one to be invented for it, as twenty years ago Alpine Clubmen, in accord with Russian surveyors, found or invented names for many of the great peaks of the Caucasus… Should [the Royal Geographical Society] resolve that, considering the length of time the title "Mount Everest" has been more or less in use in this country for Peak XV, the absence of any evidence that that individual peak is designated as, or included in the designation of Gaurisankar by the Nepalese, and the practical inconvenience (whether the name be authentic or not) of introducing a new Tibetan name such as Chomo- or Jamokangkar, it is expedient that the title Mount Everest should be generally accepted, I shall acquiesce. **Douglas W. Freshfield**

From *Nature* 24 November 1904.

50 YEARS AGO

Studies on the pharmacology of extracts of *Rauwolfia serpentina*… reported that the alkaloid… had a marked hypotensive effect which was in part due to depression of central nervous system mechanisms… Our own studies have confirmed that [the *Rauwolfia* alkaloid] reserpine diminished reflex vasomotor responses, but have also demonstrated a direct effect on the peripheral vessels independent of its nervous activity… We have found that injections of reserpine into the systemic circulation of the rabbit produce an immediate fall in systemic blood pressure. This is accompanied by an immediate rise in limb perfusion pressure instead of a fall, as would have been expected were the fall of blood pressure mediated through the nervous system. Furthermore, injection of reserpine directly into the artery of the perfused hind-limb causes immediate diminution in vasomotor tone.

From *Nature* 27 November 1954.

through Heisenberg's uncertainty principle, as one is measured more precisely the information on the other is degraded. This incompatibility severely limits the fidelity of storage and retrieval of information in a simple 'classical' memory, in which $\hat{X}_L$ and $\hat{P}_L$ are measured and these values are then imprinted on $\hat{X}_A$ and $\hat{P}_A$.

Julsgaard *et al.* have achieved a faithful copy with a more elaborate scheme, reminiscent of their recent experiment on atomic entanglement[10]. It proceeds in two steps. One of the light observables is first directly copied onto the atomic system through a non-resonant laser–atom interaction. The second step is then more akin to the classical memory operation: the other light observable is measured and the measurement result is fed back onto the atomic system, completing the memory operation.

To follow the process in more detail, imagine that the initial quantum properties of the input light pulse are described by $\hat{X}_L^{in}$ and $\hat{P}_L^{in}$, and those of the atomic sample by $\hat{X}_A^{in}$ and $\hat{P}_A^{in}$. The laser pulse crosses the cell of caesium vapour. It is not absorbed, but $\hat{X}_A$ — which is now $\hat{X}_A^{in} + \hat{P}_L^{in}$ — stores the $\hat{P}_L$ information (with a bit of added noise, owing to the initial quantum uncertainty $\hat{X}_A^{in}$). The laser observable $\hat{X}_L$ is cast into $\hat{X}_L^{in} + \hat{P}_A^{in}$. In the next step of the process, $\hat{X}_L$ is measured (destroying $\hat{P}_L$, but that is no longer important, because it is already stored in an atomic variable). The measured value is made negative and fed back onto $\hat{P}_A$ by an electronic circuit and a magnetic field acting on the atoms. This achieves two goals at once: the initial quantum noise $\hat{P}_A^{in}$ is cancelled and the observable is replaced by $-\hat{X}_L^{in}$. Finally, $\hat{X}_L^{in}$ and $\hat{P}_L^{in}$ are mapped onto $-\hat{P}_A$ and $\hat{X}_A$, completing the storage operation.

In principle, the storage operation can be reversed and a light pulse identical to the input one can be regenerated. Julsgaard *et al.* preferred instead to measure the atomic observables with additional laser pulses. Through careful calibration of the quantum noise, and by comparing the probability distributions of the input and memory observables, they assessed the storage fidelity — it is significantly higher than the best possible performance of the 'measure and imprint' classical approach. But it is still not perfect, limited by experimental imperfections and initial quantum noise on $\hat{X}_A$. The latter could be combated in more elaborate versions of the experiment by preparing the atoms initially in a 'squeezed state', with considerably reduced fluctuations on $\hat{X}_A$ (at the expense of increased ones on $\hat{P}_A$). There should then be no limit to the fidelity.

This experiment suggests a basis for a quantum-information network operating with faint laser pulses. Obviously, there is much more work to do. The fidelity should be pushed up and the storage time increased above the present value of a few milliseconds. An encouraging point is that this scheme uses rather simple elements, being based on clever ideas rather than heavy technology, and could therefore be turned into a practical device. It is also a clear demonstration that a large ensemble of atoms can be used as a quantum system — a line of research that is bound to generate many more exciting results. ■

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Evolutionary biology

Light on ancient photoreceptors

Thurston Lacalli

Early multicellular organisms had two distinct types of photoreceptor cells, apparently with different functions. How these cells combined to form modern eyes turns out to be a complicated story.

The image-forming eyes, simple eyes (ocelli) and other photoreceptor organs of animals are structurally diverse. But their photoreceptor cells are basically of two types only — either 'ciliary' or 'rhabdomeric', depending on whether they use cilia or arrays of microvilli for light reception (Fig. 1). In a study of *Platynereis*, a marine segmented worm, published in *Science*, Arendt *et al.*[1] provide convincing evidence from gene-expression studies and sequence comparisons that the last common ancestor of bilaterally symmetric animals had both types. Their proposal for the functions the two performed, specifically the role of ciliary receptors in monitoring photoperiod, advances our understanding of the ancestral condition, before the origin of divergent types of advanced, image-forming eyes.

Our own eyes, like those of other vertebrates, have ciliary photoreceptors; so does the pineal 'third eye', a structure that is buried in the brain and is involved in circadian rhythmicity, and which still, in lower vertebrates, functions directly as a photoreceptor. The various ocelli and image-forming eyes of invertebrates, in contrast, are rhabdomeric. This, for a while, provided a useful general rule that, along with embryological differences, distinguished between the two main groups of animals: protostomes (diverse worms, molluscs and arthropods) use rhabdomeric photoreceptors; deuterostomes (vertebrates and their kin) have ciliary ones.

The person most closely associated with the idea of a dichotomy is the late Richard Eakin of the University of California, Berkeley, who carried out an extensive study of comparative eye structure using the then relatively new technique of electron microscopy[2]. Exceptions to the rule do occur, and in some marine flatworm larvae even single ocelli can have both types of receptor cell[3]. The small size and sporadic occurrence of such structures has discouraged any systematic study of their function, however, so they have remained little more than anomalies in an otherwise broadly accepted general pattern.

The advantage of molecular techniques, as applied to the problem by Arendt *et al.*[1], is twofold: first, their ability to reveal gene-expression patterns in individual cells; second, the inferences one can make regarding function based on the known function of homologous genes (orthologues) in other animals. The results show that there are two forms of the gene for the photopigment opsin in *Platynereis*, one ciliary, previously unknown from protostomes, and one rhabdomeric. The former is expressed in two small clusters of apical cells with internalized cilia, located in the developing brain. The cells also express an orthologue of the *rx* gene, an upstream controller of ciliary photoreceptor differentiation in vertebrates, and either they or adjacent cells show rhythmic expression of a *bmal/cycle* gene, a key component of the circadian clock. An unanswered question is the relation between the cells that express these genes and larval apical tuft cells, which are internalized intact during development in some marine worms[4]. An assortment of other, possibly related structures — apical ciliated pits and ampullary organs — also occur in molluscan larvae[5].

Assuming that *Platynereis* does indeed preserve something of the ancestral condition (that is, of the common ancestor of protostomes and deuterostomes), the results are best explained by an early origin of two separate types of photoreceptor. Rhabdomeric ones would have been used for monitoring light direction, and ciliary ones for photoperiod. As image-forming eyes evolved,