QUANTUM PHYSICS

Tangled memories

Lene Vestergaard Hau

The latest quantum trick — mapping two entangled photon states onto two separate regions of an atomic cloud, and then retrieving them — could be a fillip for applications, among them quantum cryptography.

On page 67 of this issue, Choi *et al.*[1] recount how they store two 'entangled' photon states in a memory consisting of a cloud of cold atoms, and then, after a certain delay, retrieve those self-same states from the cloud. The optical modes are stored in spatially separated regions of a single atom cloud, but there is no reason why the technique should not be used to imprint the same quantum states on two distinct atom clouds separated by a macroscopic distance. That would allow the controlled entanglement of two distant atomic samples — a step that might be of great importance for the practical implementation of quantum protocols to generate secure keys for the transfer of information over public networks.

Choi and colleagues' experiments start off with a light pulse containing a single photon. Like most of us, this photon soon comes to a point in life — in its case, a beam splitter — at which it is faced with a choice between two paths. In such a situation, the quantum world is kinder than the classical: it allows the photon to take both paths at the same time. If we set up a light detector to monitor one of the two paths, we will register a click (a photon hit) or no click, each with a 50% chance. But say some other (possibly distant) observer sets up a detector to monitor the other path. In this case, if this second observer detects a click, that instantaneously affects our own measurement: we will detect 'no click' with 100% probability (or vice versa, an absolutely certain click if the remote observer has detected no click).

This is entanglement: the strange correlation of two spatially separated quantum states. Entangled states are hard to maintain, because interactions with the environment destroy the entanglement. As a result, they are rare in our macroscopic world. But that doesn't stop them being essential to quantum information processing, for computing, teleportation and encryption applications.

In a classical computer, information is stored in strings of bits of value 0 or 1. The quantum bits of a quantum computer, on the other hand, can be in 'superposition states': they can be 0 and 1 at the same time. Here, entanglement comes into its own. Let's say the quantum computer is set up to calculate the output value of a function that varies periodically with its input value (a sine wave, for example); we wish to find that period. The quantum computation leaves the system in a superposition of matched pairs, in which the output register holds the function value for the corresponding input.

The two registers are in fact entangled: a measurement of the output register will immediately affect the input register. For a periodic function, in which many input values correspond to a particular output value, the input register ends up in a superposition of precisely these inputs. After just one run-through of the calculation, therefore, global information

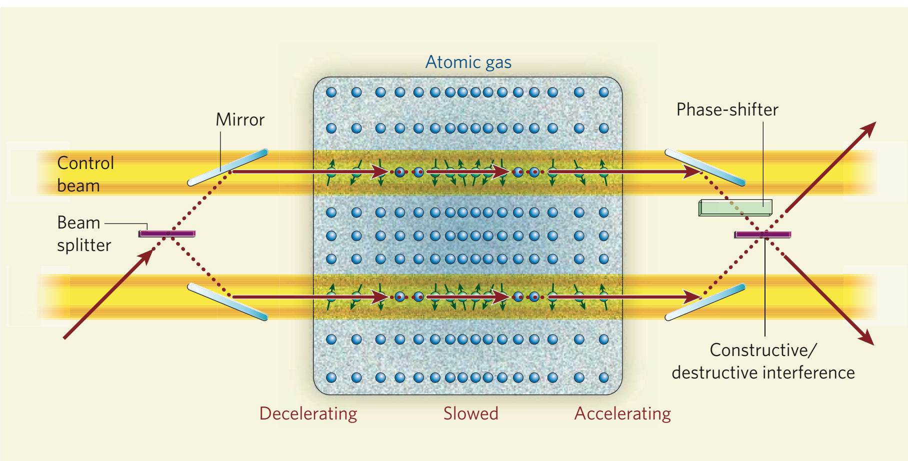

Figure 1 | Light split and slowed. In Choi and colleagues' experimental apparatus[1], a light pulse (red arrow) is split into two entangled states and fed into an atomic gas. There, under the influence of controlling laser beams, the split pulse is slowed, and the two entangled quantum states are imprinted onto two separate regions of the gas — effectively creating entanglement between the atoms of these regions. The light is then extinguished, and after a delay the photonic quantum states are regenerated from the information stored in the atoms. The amount of remaining entanglement is measured through the degree of constructive or destructive interference when the regenerated optical fields are recombined.

50 & 100 YEARS AGO

50 YEARS AGO

"A three-dimensional model of the myoglobin molecule obtained by X-ray analysis." By Drs J. C. Kendrew *et al.* — Until five years ago, no one knew how, in practice, the complete structure of a crystalline protein might be found by X-rays, and it was realized that the methods then in vogue among protein crystallographers could at best give the most sketchy indications about the structure of the molecule. This situation was transformed by the discovery, made by Perutz and his colleagues, that heavy atoms could be attached to protein molecules in specific sites and that the resulting complexes gave diffraction patterns sufficiently different from normal to enable a classical method of structure analysis, the so-called 'method of isomorphous replacement', to be used to determine the relative phases of the reflexions ... The present article describes the application, at low resolution, of the isomorphous replacement method in three dimensions to type *A* crystals of sperm whale myoglobin. The result is a three-dimensional Fourier, or electron-density, map of the unit cell, which for the first time reveals the general nature of the tertiary structure of a protein molecule ... Perhaps the most remarkable features of the molecule are its complexity and its lack of symmetry. The arrangement ... is more complicated than has been predicated by any theory of protein structure.

From *Nature* 8 March 1958

100 YEARS AGO

It is reported by The Hague correspondent of the *Globe* (March 3) that Prof. Kamerlingh Onnes, professor of physics in the University of Leyden, has succeeded in liquefying helium.

ALSO:

In the report of the Maidstone Museum, Library, and Art Gallery for 1907, attention is directed to the unprecedentedly large number of visitors during the year.

From *Nature* 5 March 1908.

about the function — its period — is contained in the input register. After some 'fiddling', this period can be read out with many fewer operations than a classical computer requires[2]. (In a classical calculation we would have to run the computation many times, once for each input value, to slowly, step by step, build up global information about the function.)

Encoding this information in material quantum states, such as those of atomic clouds, is a particularly promising avenue towards implementing quantum-computational schemes: the interactions between atoms can be strong, and processing (through controlled changes to the quantum states) can happen fast. Long-distance transmission of the resulting output quantum states, on the other hand, works better with light: light can travel fast and with minimal losses in optical fibres. Reliable and efficient ways of mapping quantum information between light and matter are therefore an essential component of any quantum information network.

In their experiments, Choi *et al.*[1] achieve this transfer using 'slow light'[3]. Under particular conditions dictated by quantum mechanics, the speed of a light pulse that has been injected into an atom cloud illuminated by a control laser can be reduced by many orders of magnitude. As the pulse slows, its spatial extent shrinks, and it ultimately fits snugly inside the atom cloud (Fig. 1). The pulse affects the internal states of atoms within its localized region, creating a hologram-like imprint of itself in the atom cloud. If the control laser is turned off, the light pulse is halted and extinguished, but its atomic imprint remains in the cloud. If the control laser is turned back on, the same process runs backwards: the light pulse is regenerated and moves on, exits the atom cloud and speeds back up. Such storage of optical information has been demonstrated for classical light pulses containing many photons[4,5] and for single-photon light pulses[6,7].

The authors show that the entanglement of two light fields also survives such storage. They create their single-photon pulse by generating a single atomic excitation in a separate 'source' atom cloud, using the slow-light effect to read it out. The entangled optical modes generated at the beam splitter are injected into the main atomic sample, separated by 1 millimetre. After a microsecond, the authors are able to regenerate the optical fields. They then introduce a phase shift into one before the two modes recombine at a second beam splitter. Depending on the phase shift introduced, constructive or destructive quantum interference between the two optical paths is measured at a detector after the second beam splitter. The contrast of the fringes obtained as the phase is varied tells us the quality of the entanglement.

So what is the next step? Separate control of the phase relationship between the two optical modes' input to the atom cloud would allow the controlled storage and revival of actual quantum bits. Choi *et al.*[1] use cold atoms for their experiments, laser cooled to about 125 microkelvin above absolute zero to avoid thermal smearing of the stored holographic imprints; but it would be interesting to cool things down further, forming the phase-coherent state of atomic matter known as a Bose–Einstein condensate, which offers much-increased possibilities for storage and controlled processing[8]. The storage of entangled optical fields in two separated atom clouds also needs to be formally demonstrated. Such entanglement would allow the efficient sharing of quantum keys for secure encryption[9], and the transfer (teleportation) of quantum bits between two atomic clouds by simple transmission of pairs of classical bits[10].

Will any or all of this ever get to a stage at which it can be used in practical devices? That remains to be seen. We can state, however, that a century after quantum mechanics was discovered, the possibilities it offers continue to boggle our minds. ■

Lene Vestergaard Hau is in the Lyman Laboratory, Physics Department, Harvard University, 17 Oxford Street, Cambridge, Massachusetts 02138, USA.
e-mail: hau@physics.harvard.edu

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NEUROSCIENCE

A complex in psychosis

Solomon H. Snyder

The molecular basis of psychoses such as schizophrenia remains largely mysterious. The interaction between two of the brain receptors involved adds to evidence that will help in the search for explanations.

This is a story that involves three types of receptor in the brain that influence human perception and behaviour (those for the neurotransmitters dopamine, serotonin and glutamate), and the drugs that block or enhance their activity. Such drugs are used by researchers to investigate the causes of psychotic disorders such as schizophrenia, and by clinicians to treat patients. Classical antipsychotic drugs, designated 'typical neuroleptics', act predominantly by blocking dopamine D2 receptors. A new generation of more effective 'atypical neuroleptics' also blocks a subtype of serotonin receptor known as 5-HT$_{2A}$, or more simply as 2AR. And last year we had the promising report[1] of a drug that mimics the effect of glutamate at a subtype of one of its receptors, metabotropic glutamate receptor 2 (mGluR2), and that seems to be as effective as atypical neuroleptics.

This is the background against which the paper by González-Maeso *et al.*[2] appears (page 93 of this issue): these authors show that

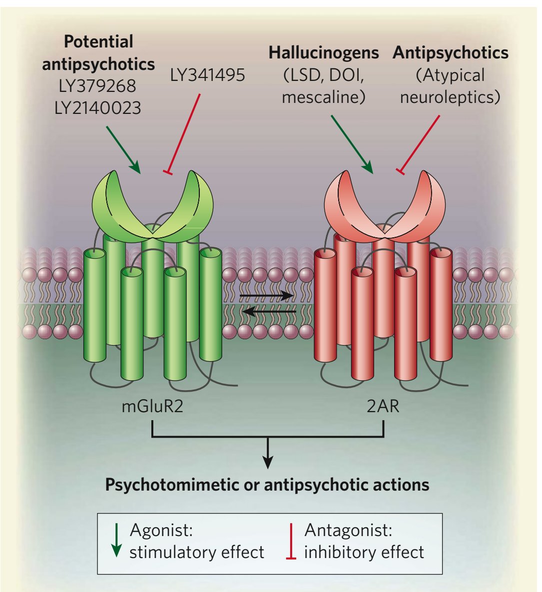

Figure 1 | Receptor interaction. González-Maeso *et al.*[2] find that the metabotropic glutamate receptor 2 (mGluR2) and serotonin 5-HT$_{2A}$ receptor (2AR) physiologically bind each other, leading to reciprocal regulation of their functions. Agonists that stimulate mGluR2 are antipsychotic, whereas 2AR agonists, such as hallucinogens, have the opposite effect. It is conceivable that the clinically significant anti-schizophrenic effects of LY2140023, an mGluR2 agonist[1], derive from reducing the excessive — and hence hallucinogen-like — activity of 2AR. DOI, 2,5-dimethoxy-4-iodoamphetamine.