A similar replacement of the active subset is not apparent in the dentate gyrus, which suggests that the change in the CA3 code is triggered by direct projections from entorhinal grid cells to the CA3 (*32*).

Pattern separation in the dentate gyrus is thus different from separation processes in the cerebellum (*10*, *11*), where signals from the brain stem spread out on a layer of granule cells whose cell numbers exceed those of the input layer by a factor of several million. The number of granule cells in the dentate gyrus and pyramidal cells in the CA3 only marginally outnumbers the projection neurons from layer II of the entorhinal cortex [in the rat, 1,000,000, 300,000 and 200,000, respectively (*15*, *35*, *36*)], which suggests that the same hippocampal cells must participate in many representations even when the population activity is sparse (*13*, *14*). In such networks, orthogonalization of coincidence patterns may be more effective.

The decorrelated firing of the dentate cells contrasts with the invariant discharge structure of grid cells upstream in the medial entorhinal cortex (*30*–*32*) (Fig. 4). The reduction in spatiotemporal coincidence could be derived from the lateral entorhinal cortex, but not by a straightforward relay mechanism, because cells in this area do not exhibit reliable place modulation (*37*). It is thus likely that many of the underlying computations take place within the dentate gyrus itself. The use of a dedicated neuronal population for orthogonalization of small differences in input to the CA fields enables the hippocampal network to encode the full variety of experience in a more diversified manner than what could be accomplished with attractor networks alone.

References and Notes

1. B. L. McNaughton, L. Nadel, in *Neuroscience and Connectionist Theory*, M. A. Gluck and D. E. Rumelhart, Eds. (Lawrence Erlbaum, Hillsdale, NJ, 1989), pp. 1–63.
2. A. Treves, E. T. Rolls, *Hippocampus* **2**, 189 (1992).
3. R. C. O'Reilly, J. L. McClelland, *Hippocampus* **4**, 661 (1994).
4. P. E. Gilbert, R. P. Kesner, I. Lee, *Hippocampus* **11**, 626 (2001).
5. D. Marr, *Philos. Trans. R. Soc. Lond. B Biol. Sci.* **262**, 23 (1971).
6. M. E. Hasselmo, E. Schnell, E. Barkai, *J. Neurosci.* **15**, 5249 (1995).
7. M. Tsodyks, *Hippocampus* **9**, 481 (1999).
8. K. Nakazawa *et al.*, *Science* **297**, 211 (2002).
9. I. Lee, D. Yoganarasimha, G. Rao, J. J. Knierim, *Nature* **430**, 456 (2004).
10. D. Marr, *J. Physiol.* **202**, 437 (1969).
11. J. Albus, *Math. Biosci.* **10**, 25 (1971).
12. P. Chadderton, T. W. Margrie, M. Hausser, *Nature* **428**, 856 (2004).
13. M. W. Jung, B. L. McNaughton, *Hippocampus* **3**, 165 (1993).
14. M. K. Chawla *et al.*, *Hippocampus* **15**, 579 (2005).
15. D. G. Amaral, N. Ishizuka, B. Claiborne, *Prog. Brain Res.* **83**, 1 (1990).
16. J. O'Keefe, J. Dostrovsky, *Brain Res.* **34**, 171 (1971).
17. R. U. Muller, J. L. Kubie, J. B. Ranck Jr., *J. Neurosci.* **7**, 1935 (1987).
18. R. U. Muller, J. L. Kubie, *J. Neurosci.* **7**, 1951 (1987).
19. G. J. Quirk, R. U. Muller, J. L. Kubie, *J. Neurosci.* **10**, 2008 (1990).
20. E. Bostock, R. U. Muller, J. L. Kubie, *Hippocampus* **1**, 193 (1991).
21. E. J. Markus *et al.*, *J. Neurosci.* **15**, 7079 (1995).
22. C. Lever, T. Wills, F. Cacucci, N. Burgess, J. O'Keefe, *Nature* **416**, 90 (2002).
23. T. J. Wills, C. Lever, F. Cacucci, N. Burgess, J. O'Keefe, *Science* **308**, 873 (2005).
24. S. Leutgeb *et al.*, *Science* **309**, 619 (2005).
25. Materials and Methods and other supporting material are available on *Science* Online.
26. J. K. Leutgeb *et al.*, *Neuron* **48**, 345 (2005).
27. D. A. Henze, L. Wittner, G. Buzsáki, *Nat. Neurosci.* **5**, 790 (2002).
28. K. D. Harris, J. Csicsvari, H. Hirase, G. Dragoi, G. Buzsáki, *Nature* **424**, 552 (2003).
29. R. M. Hayman, S. Chakraborty, M. I. Anderson, K. J. Jeffery, *Eur. J. Neurosci.* **18**, 2825 (2003).
30. M. Fyhn, S. Molden, M. P. Witter, E. I. Moser, M.-B. Moser, *Science* **305**, 1258 (2004).
31. T. Hafting, M. Fyhn, S. Molden, M.-B. Moser, E. I. Moser, *Nature* **436**, 801 (2005).
32. M. H. Fyhn, T. F. Hafting, A. Treves, E. I. Moser, M.-B. Moser, *Nature,* in press.
33. S. Leutgeb, J. K. Leutgeb, A. Treves, M.-B. Moser, E. I. Moser, *Science* **305**, 1295 (2004).
34. A. Vazdarjanova, J. F. Guzowski, *J. Neurosci.* **24**, 6489 (2004).
35. P. R. Rapp, P. S. Deroche, Y. Mao, R. D. Burwell, *Cereb. Cortex* **12**, 1171 (2002).
36. B. D. Boss, G. M. Peterson, W. M. Cowan, *Brain Res.* **338**, 144 (1985).
37. E. L. Hargreaves, G. Rao, I. Lee, J. J. Knierim, *Science* **308**, 1792 (2005).

38. We thank A. Treves, C. A. Barnes, and M. R. Mehta for discussion and A. M. Amundsgard, K. Haugen, K. Jenssen, E. Sjulstad, R. Skjerpeng, and H. Waade for technical assistance. This work was supported by a Centre of Excellence grant from the Norwegian Research Council.

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2 October 2006; accepted 15 December 2006
10.1126/science.1135801

REPORTS

Experimental Realization of Wheeler's Delayed-Choice Gedanken Experiment

Vincent Jacques,[1] E Wu,[1,2] Frédéric Grosshans,[1] François Treussart,[1] Philippe Grangier,[3] Alain Aspect,[3] Jean-François Roch[1]*

Wave-particle duality is strikingly illustrated by Wheeler's delayed-choice gedanken experiment, where the configuration of a two-path interferometer is chosen after a single-photon pulse has entered it: Either the interferometer is closed (that is, the two paths are recombined) and the interference is observed, or the interferometer remains open and the path followed by the photon is measured. We report an almost ideal realization of that gedanken experiment with single photons allowing unambiguous which-way measurements. The choice between open and closed configurations, made by a quantum random number generator, is relativistically separated from the entry of the photon into the interferometer.

Young's double-slit experiment, realized with particles sent one at a time through an interferometer, is at the heart of quantum mechanics (*1*). The striking feature is that the phenomenon of interference, interpreted as a wave following two paths simultaneously, is incompatible with our common-sense representation of a particle following one route or the other but not both. Several single-photon interference experiments (*2*–*6*) have confirmed the wave-particle duality of the light field. To understand their meaning, consider the single-photon interference experiment sketched in Fig. 1. In the closed interferometer configuration, a single-photon pulse is split by a first beamsplitter BS_{input} of a Mach-Zehnder interferometer and travels through it until a second beamsplitter BS_{output} recombines the two interfering arms. When the phase shift Φ between the two arms is varied, interference appears as a modulation of the detection probabilities at output ports 1 and 2, respectively, as $\cos^2 \Phi$ and $\sin^2 \Phi$. This result is the one expected for a wave, and as Wheeler pointed out, "[this] is evidence … that each ar-

[1]Laboratoire de Photonique Quantique et Moléculaire, Ecole Normale Supérieure de Cachan, UMR CNRS 8537, 94235 Cachan, France. [2]Key Laboratory of Optical and Magnetic Resonance Spectroscopy, East China Normal University, 200062 Shanghai, China. [3]Laboratoire Charles Fabry de l'Institut d'Optique, Campus Polytechnique, UMR CNRS 8501, 91127 Palaiseau, France.

*To whom correspondence should be addressed. E-mail: roch@physique.ens-cachan.fr

riving light quantum has arrived by both routes" (*7*). If BS_{output} is removed (the open configuration), each detector D1 or D2 on the output ports is then associated with a given path of the interferometer, and, provided one uses true single-photon light pulses, "[either] one counter goes off, or the other. Thus the photon has traveled only one route" (*7*). Such an experiment supports Bohr's statement that the behavior of a quantum system is determined by the type of measurement performed on it (*8*). Moreover, it is clear that for the two complementary measurements considered here, the corresponding experimental settings are mutually exclusive; that is, BS_{output} cannot be simultaneously present and absent.

In experiments where the choice between the two settings is made long in advance, one could reconcile Bohr's complementarity with Einstein's local conception of the physical reality. Indeed, when the photon enters the interferometer, it could have received some "hidden information" on the chosen experimental configuration and could then adjust its behavior accordingly (*9*). To rule out that too-naïve interpretation of quantum mechanical complementarity, Wheeler proposed the "delayed-choice" gedanken experiment in which the choice of which property will be observed is made after the photon has passed BS_{input}: "Thus one decides the photon shall have come by one route or by both routes after it has already done its travel" (*7*).

Since Wheeler's proposal, several delayed-choice experiments have been reported (*10–15*). However, none of them fully followed the original scheme, which required the use of the single-particle quantum state as well as relativistic space-like separation between the choice of interferometer configuration and the entry of the particle into the interferometer. We report the realization of such a delayed-choice experiment in a scheme close to the ideal original proposal (Fig. 1). The choice to insert or remove BS_{output} is randomly decided through the use of a quantum random number generator (QRNG). The QRNG is located close to BS_{output} and is far enough from the input so that no information about the choice can reach the photon before it passes through BS_{input}.

Our single-photon source, previously developed for quantum key distribution (*16*, *17*), is based on the pulsed, optically excited photoluminescence of a single nitrogen-vacancy (N-V) color center in a diamond nanocrystal (*18*). At the single-emitter level, these photoluminescent centers, which can be individually addressed with the use of confocal microscopy (*19*), have shown unsurpassed efficiency and photostability at room temperature (*20*, *21*). In addition, it is possible to obtain single photons with a well-defined polarization (*16*, *22*).

The delayed-choice scheme is implemented as follows. Linearly polarized single photons are sent by a polarization beamsplitter BS_{input} through an interferometer (length 48 m) with two spatially separated paths associated with orthogonal S and P polarizations (Fig. 2). The movable output beamsplitter BS_{output} consists of the combination of a half-wave plate, a polarization beamsplitter BS′, an electro-optical modulator (EOM) with its optical axis oriented at 22.5° from input polarizations, and a Wollaston prism. The two beams of the interferometer, which are spatially separated and orthogonally polarized, are first overlapped by BS′ but can still be unambiguously identified by their polarization. Then, the choice between the two interferometer configurations, closed or open, is realized with the EOM, which can be switched between two different configurations within 40 ns by means of a homebuilt fast driver (*16*): Either no voltage is applied to the EOM, or its half-wave voltage V_π is applied to it. In the first case, the situation corresponds to the removal of BS_{output} and the two paths remain uncombined (open configuration). Because the original S and P polarizations of the two paths are oriented along prism polarization eigenstates, each "click" of one detector D1 or D2 placed on the output ports is associated with a specific path (path 1 or path 2, respectively). When the V_π voltage is applied, the EOM is equivalent to a half-wave plate that rotates the input polarizations by an angle of 45°. The prism then recombines the two rotated polarizations that have traveled along different optical paths, and interference appears on the two output ports. We then have the closed interferometer configuration (*22*).

To ensure the relativistic space-like separation between the choice of the interferometer configuration and the passage of the photon at BS_{input}, we configured the EOM switching process to be randomly decided in real time by the QRNG located close to the output of the interferometer (48 m from BS_{input}). The random number is generated by sampling the amplified shot noise of a white-light beam. Shot noise is an intrinsic quantum random process, and its value at a given time cannot be predicted (*23*). The timing of the experiment ensures the required relativistic space-like separation (*22*). Then, no information about the interferometer configuration choice can reach the photon before it enters the interferometer.

The single-photon behavior was first tested using the two output detectors feeding single and

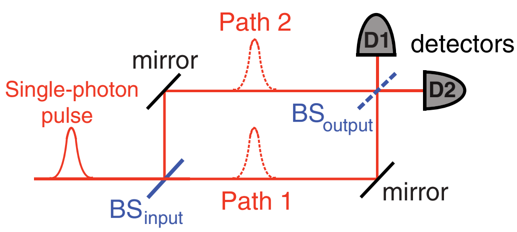

Fig. 1. Wheeler's delayed-choice gedanken experiment proposal. The choice to introduce or remove beamsplitter BS_{output} (closed or open configuration) is made only after the passage of the photon at BS_{input}, so that the photon entering the interferometer "cannot know" which of the two complementary experiments (path difference versus which-way) will be performed at the output.

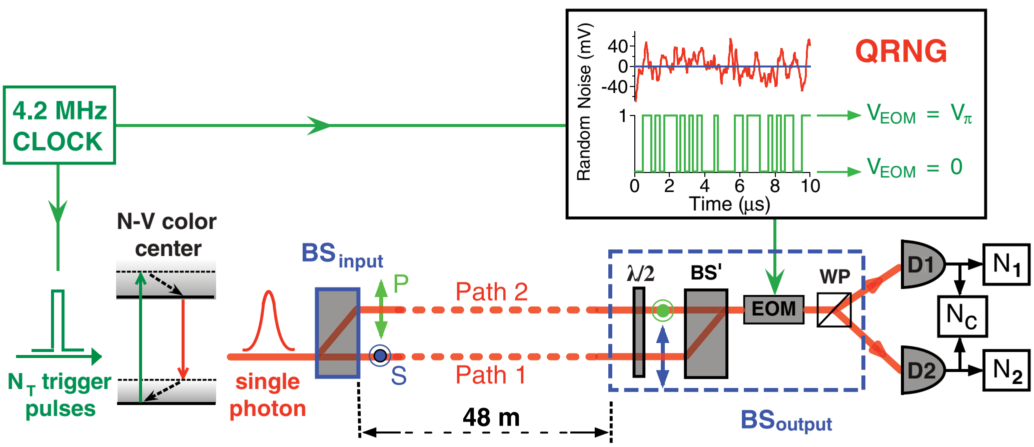

Fig. 2. Experimental realization of Wheeler's gedanken experiment. Single photons emitted by a single N-V color center are sent through a 48-m polarization interferometer, equivalent to a time of flight of about 160 ns. A binary random number 0 or 1, generated by the QRNG, drives the EOM voltage between $V = 0$ and $V = V_\pi$ within 40 ns, after an electronic delay of 80 ns. Two synchronized signals from the clock are used to trigger the single-photon emission and the QNRG. In the laboratory frame of reference, the random choice between the open and the closed configuration is made simultaneously with the entry of the photon into the interferometer. Taking advantage of the fact that the QNRG is located at the output of the interferometer, such timing ensures that the photon enters the future light cone of the random choice when it is at about the middle of the interferometer, long after passing BS_{input}.

coincidence counters with BS_{output} removed (open configuration). We used an approach similar to the one described in (*2*) and (*6*). Consider a run corresponding to N_T trigger pulses applied to the emitter, with N_1 counts detected in path 1 of the interferometer by D1, N_2 counts detected in path 2 by D2, and N_C detected coincidences corresponding to joint photodetections on D1 and D2 (Fig. 2). Any description in which light is treated as a classical wave, such as the semiclassical theory with quantized photodetectors (*24*), predicts that these numbers of counts should obey the inequality

$$\alpha = \frac{N_C \times N_T}{N_1 \times N_2} \geq 1 \qquad (1)$$

Violation of this inequality thus gives a quantitative criterion that characterizes nonclassical behavior. For a single-photon wavepacket, quantum optics predicts perfect anticorrelation (i.e., $\alpha = 0$) in agreement with the intuitive image that a single particle cannot be detected simultaneously in the two paths of the interferometer (*2*). We measured $\alpha = 0.12 \pm 0.01$, hence we are indeed close to the pure single-photon regime. The nonideal value of the α parameter is due to residual background photoluminescence of the diamond sample and to the two-phonon Raman scattering line, which both produce uncorrelated photons with Poissonian statistics (*6*).

With single-photon pulses in the open configuration, we expected each detector D1 and D2 to be unambiguously associated with a given path of the interferometer. To test this point, we evaluated the "which-way" information parameter $I = (N_1 - N_2)/(N_1 + N_2)$ (*25*–*28*) by blocking one path (e.g., path 2) and measuring the counting rates at D1 and D2. A value of I higher than 0.99 was measured, limited by detector dark counts and residual imperfections of the optical components. The same value was obtained when the other path was blocked (e.g., path 1). In the open configuration, we thus have an almost ideal which-way measurement.

The delayed-choice experiment itself is performed with the EOM randomly switched for each photon sent into the interferometer, corresponding to a random choice between the open and closed configurations. The phase shift Φ between the two interferometer arms is varied by tilting the second polarization beamsplitter BS′ with a piezoelectric actuator (PZT). For each photon, we recorded the chosen configuration, the detection events, and the PZT position. All raw data were saved in real time and were processed only after a run was completed. For each PZT position, detection events on D1 and D2 corresponding to each configuration were sorted (Fig. 3). In the closed configuration, we observed interference with 0.94 visibility. We attribute the departure from unity to an imperfect overlap of the two interfering beams. In the open configuration, interference totally disappears, as evidenced by the absence of modulation in the two output ports when the phase shift Φ was varied. We checked that in the delayed-choice configuration, parameters α and I kept the same values as measured in the preliminary tests presented above.

Our realization of Wheeler's delayed-choice gedanken experiment demonstrates that the behavior of the photon in the interferometer depends on the choice of the observable that is measured, even when that choice is made at a position and a time such that it is separated from the entrance of the photon into the interferometer by a space-like interval. In Wheeler's words, as no signal traveling at a velocity less than that of light can connect these two events, "we have a strange inversion of the normal order of time. We, now, by moving the mirror in or out have an unavoidable effect on what we have a right to say about the already past history of that photon" (*7*). Once more, we find that nature behaves in agreement with the predictions of quantum mechanics even in surprising situations where a tension with relativity seems to appear (*29*).

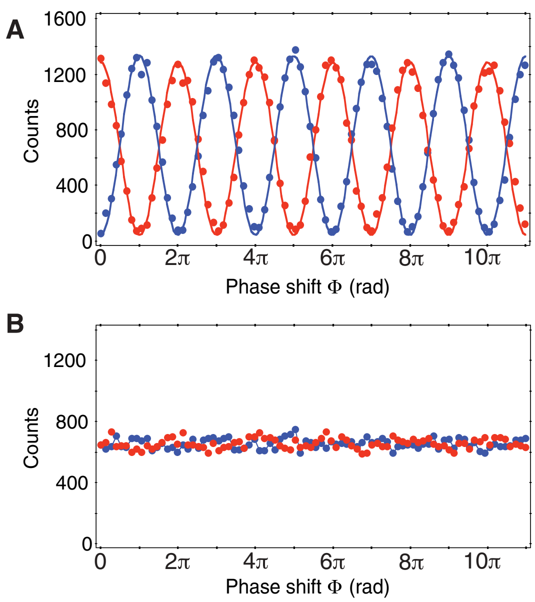

Fig. 3. Results of the delayed-choice experiment. The phase shift Φ (indicated with arbitrary origin) is varied by tilting BS′. Each point, recorded with acquisition time of 1.9 s, corresponds to the detection of about 2600 photons. The detector dark counts, 59 s^{-1} for D1 (blue points) and 70 s^{-1} for D2 (red points), have been subtracted from the data. (**A**) Cases when V_π is applied on the EOM (closed configuration); interference with 94% visibility is obtained. (**B**) Cases when no voltage is applied on the EOM (open configuration); no interference is observed and equal detection probabilities (0.50 ± 0.01) on the two output ports are measured, corresponding to full knowledge of the complementary which-way information (I parameter greater than 99%).

References and Notes

1. R. P. Feynman, R. B. Leighton, M. L. Sands, *Lectures on Physics* (Addison-Wesley, Reading, MA, 1965).
2. P. Grangier, G. Roger, A. Aspect, *Europhys. Lett.* **1**, 173 (1986).
3. F. Jelezko, A. Volkmer, I. Popa, K. K. Rebane, J. Wrachtrup, *Phys. Rev. A* **67**, 041802 (2003).
4. A. Zeilinger, G. Weihs, T. Jennewein, M. Aspelmeyer, *Nature* **433**, 230 (2005).
5. T. Aichele, U. Herzog, M. Scholtz, O. Benson, *AIP Conf. Proc.* **750**, 35 (2005).
6. V. Jacques *et al.*, *Eur. Phys. J. D* **35**, 561 (2005).
7. J. A. Wheeler, in *Quantum Theory and Measurement*, J. A. Wheeler, W. H. Zurek, Eds. (Princeton Univ. Press, Princeton, NJ, 1984), pp. 182–213.
8. N. Bohr, in *Quantum Theory and Measurement*, J. A. Wheeler, W. H. Zurek, Eds. (Princeton Univ. Press, Princeton, NJ, 1984), pp. 9–49.
9. G. Greenstein, A. G. Zajonc, *The Quantum Challenge* (Jones and Bartlett, Sudbury, MA, 1997).
10. C. O. Alley, O. G. Jacubowicz, W. C. Wickes, in *Proceedings of the Second International Symposium on the Foundations of Quantum Mechanics*, H. Narani, Ed. (Physics Society of Japan, Tokyo, 1987), pp. 36–47.
11. T. Hellmut, H. Walther, A. G. Zajonc, W. Schleich, *Phys. Rev. A* **72**, 2533 (1987).
12. J. Baldzuhn, E. Mohler, W. Martienssen, *Z. Phys. B* **77**, 347 (1989).
13. B. J. Lawson Daku *et al.*, *Phys. Rev. A* **54**, 5042 (1996).
14. Y.-H. Kim, R. Yu, S. P. Kulik, Y. Shih, M. O. Scully, *Phys. Rev. Lett.* **84**, 1 (2000).
15. T. Kawai *et al.*, *Nucl. Inst. Methods A* **410**, 259 (1998).
16. A. Beveratos *et al.*, *Phys. Rev. Lett.* **89**, 187901 (2002).
17. R. Alléaume *et al.*, *N. J. Phys.* **6**, 92 (2004).
18. A. Beveratos *et al.*, *Eur. Phys. J. D* **18**, 191 (2002).
19. A. Gruber *et al.*, *Science* **276**, 2012 (1997).
20. C. Kurtsiefer, S. Mayer, P. Zarda, H. Weinfurter, *Phys. Rev. Lett.* **85**, 290 (2000).
21. R. Brouri, A. Beveratos, J.-P. Poizat, P. Grangier, *Opt. Lett.* **25**, 1294 (2000).
22. See supporting material on *Science* Online.
23. H.-A. Bachor, T. C. Ralph, *A Guide to Experiments in Quantum Optics* (Wiley-VCH, Weinheim, Germany, 2004).
24. W. E. Lamb, M. O. Scully, in *Polarization, Matière et Rayonnement, Volume in Honour of A. Kastler* (Presses Universitaires de France, Paris, 1969), pp. 363–369.
25. P. Grangier, thesis, Institut d'Optique et Université Paris 11 (1986); available at http://tel.ccsd.cnrs.fr/tel-00009436.
26. B.-G. Englert, *Phys. Rev. Lett.* **77**, 2154 (1996).
27. S. Durr, T. Nonn, G. Rempe, *Phys. Rev. Lett.* **81**, 5705 (1998).
28. P. D. Schwindt, P. G. Kwiat, B.-G. Englert, *Phys. Rev. A* **60**, 4285 (1999).
29. J. S. Bell, *Speakable and Unspeakable in Quantum Mechanics* (Cambridge Univ. Press, Cambridge, 1987).
30. We thank A. Clouqueur and A. Villing for the realization of the electronics of the experiment, J.-P. Madrange for the mechanical realization of the interferometer, and A. Browaeys, L. Jacubowiez, and D. Chauvat for their constant help and many enlightening discussions. Supported by Institut Universitaire de France.

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13 October 2006; accepted 3 January 2007
10.1126/science.1136303