Make It Quantum and Continuous
Philippe Grangier
Science **332**, 313 (2011);
DOI: 10.1126/science.1204814

enabling them to respond readily to an array of incoming signals. Roy *et al*. used receptors of different signaling pathways, tagged with fluorescent proteins, to study their distribution in cytonemes of developing *Drosophila* tissues. They found that in the eye primordium, one receptor, the epidermal growth factor receptor (EGFR), was present only in extensions that pointed posteriorly (to the back). Although cytonemes extending in the dorsoventral (toward the belly) directions were present in these cells, they did not contain fluorescent EGFR. To test whether an individual cell was able to localize different receptors to distinct cytonemes, the authors expressed two different, color-tagged receptors in the air sac primordium, which lies on a structure called the wing imaginal disc: green Tkv, a version of the bone morphogenetic protein (BMP)/Decapentaplegic (Dpp) type I receptor; and red Btl, a cherry-tagged version of the receptor for the fibroblast growth factor (FGF) signal. Then they analyzed the distribution of receptors. They found that cytonemes contained either green or red punctae, suggesting that the receptors Tkv and Btl segregate to separate types of cytonemes.

These findings paint the following picture: Cells sense a given signaling molecule (ligand) on their surface, send out long filopodia, and then sort receptors to these extensions according to the ligand that induced them in the first place. Such extensions might then establish and maintain a connection to the cell, which acts as the signal source, giving them stability and the ability to send signals in a specific direction. In a previous study (*2*), researchers observed transport of EGFRs from the filopodial tip to the base, so it is conceivable that cytonemes likewise transport receptor-ligand complexes back to the cell body.

Almost nothing is known about cytoneme function, despite their initial discovery more than a decade ago (*3*) and recent advances on understanding where cytonemes form and what receptors they express. Hsiung *et al*. (*4*) had proposed that cytonemes in the *Drosophila* wing are used in ferrying Dpp, an important protein morphogen involved in fruit fly development, from source to target cells; the extensions are thus used to determine a cell's distance to the source. However, investigators have proposed several other models for distributing positional information, such as morphogen gradients established by facilitated diffusion, in combination with concentration-dependent responses ("readouts"). In the developing air sac primordium, studies have shown that FGF signaling triggers cell migration (*5*, *6*), possibly by FGF-transporting filopodia that bring activated FGF receptors to the cell bodies. Studies have also suggested that Notch-Delta signaling occurs on filopodial cell contacts between non-neighboring cells of the notum, the dorsal portion of an insect's thoracic segment (*7*). Clearly, a role in cell-to-cell signaling is emerging. At present, however, no genetic tools exist to specifically remove cytonemes and analyze the ensuing functional consequences.

Roy *et al*.'s description of specific cytoneme types raises a number of intriguing questions. For example, how do cells sort different receptors into different types of cytonemes? How can cytonemes be directed or stabilized specifically along an ascending signal gradient? Such new questions, however, should not distract the field from resolving the fundamental issue of whether cytonemes have anything to do with morphogen-mediated patterning.

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10.1126/science.1205971

PHYSICS

Make It Quantum and Continuous

Philippe Grangier

Robust teleportation of a fragile Schrödinger's-cat state was achieved with nonclassical wave-like states of light.

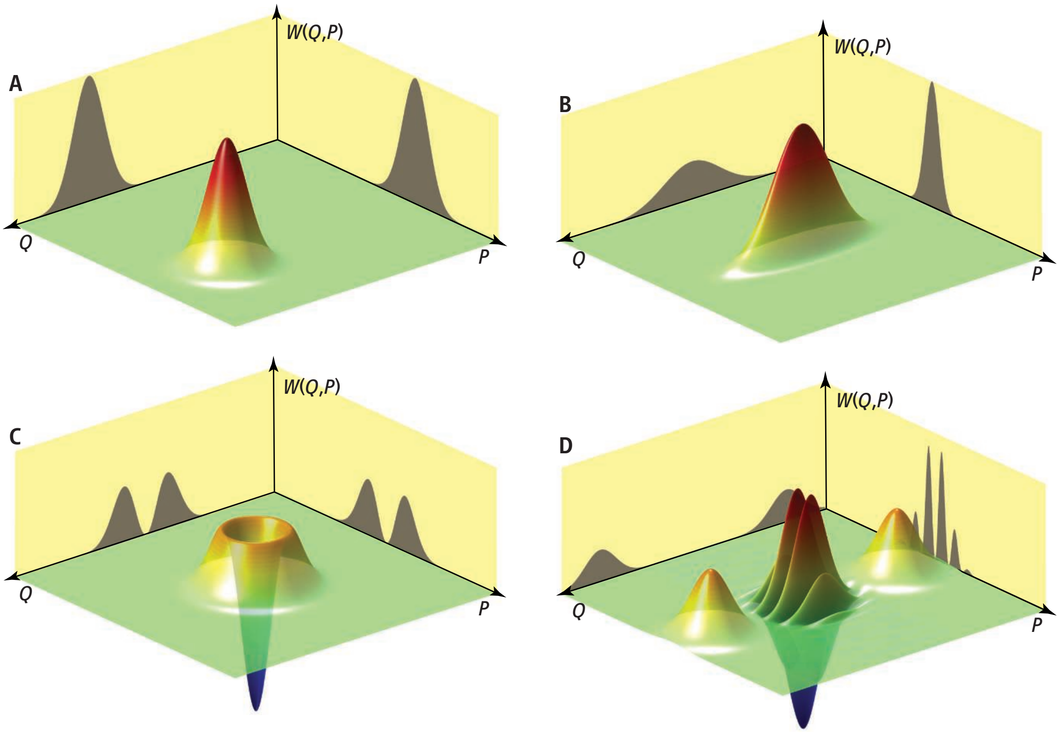
Quantum light looks like a mysterious thing: Is it wave, or particle, or both, or neither? Since the very beginning of quantum optics, physicists have been looking for graphical ways to represent the quantum state of light in order to understand it better. One can then visualize quite surprising quantum objects, such as the so-called Schrödinger's-cat state: In classical terms, it would be an oscillation having two opposite phases at the same time, like the famous cat being both living and dead. Such exotic quantum states can now be prepared in the lab, and even better, they can be teleported—that is, destroyed in one place and recreated in another one, as shown by Lee *et al*. (*1*) on page 330 of this issue.

But how to visualize what is going on? One way is by using phase space—in other words, to represent in Cartesian coordinates the sine and cosine components of the quantized electric field, which are similar to the position Q and momentum P of a quantum harmonic oscillator. The quantities Q and P obey the Heisenberg Principle—they cannot be known simultaneously with high accuracy. A best compromise is a so-called Glauber's coherent state, where the variances of Q and P are equal and take a value usually called the "vacuum noise level."

Institut d'Optique, 91127 Palaiseau, France. E-mail: philippe.grangier@institutoptique.fr

More interestingly, a "squeezed state" can be created by using a nonlinear crystal (an optical parametric down-converter), which turns a single photon into a pair of photons of lower energy. The variance of one variable (for example, P) can be made smaller than vacuum noise, at the expense of the variance of the other variable, Q, getting larger (*2*). If one now considers two separate beams 1 and 2, the pairs of continuous variables (Q_1, P_1) and (Q_2, P_2) can be entangled—their measurement outcomes are not independent but show very strong quantum correlations. For the beams to be entangled, it is sufficient that the quantities ($Q_1 - Q_2$) and ($P_1 + P_2$) simultaneously have a small variance. Such a continuous-variable entangled state can been used to teleport a coherent state (*3*)—that is, to destroy it and then to recreate it remotely—using the entangled beams as a resource for transmission (*4*–*6*).

To visualize these objects, it is convenient to introduce a mathematical tool called the Wigner function $W(Q, P)$, which is very close to being a probability distribution of the electric field in the (Q, P) plane—except that it can take on negative values. For a coherent state, $W(Q, P)$ is a cylindrically symmetric Gaussian function that peaks at coordinates that are just the average values of the sine and cosine components of the electric field. The width of the peak corresponds to the vacuum noise



Negative values and positive results. The Wigner function is a way to describe how "quantum" a light pulse is. Progressing from most classical to most quantum, the Wigner functions are shown for (**A**) the coherent state, (**B**) a squeezed state, (**C**) the single-photon state, and (**D**) a Schrödinger's-cat state. The projections or "shadows" of the Wigner function (shown on the sides) are the measured probability distributions of the quantum continuous variables *Q* or *P*. The Wigner function is a Gaussian function for (A) and (B), but it takes negative values for the strongly quantum states (C) and (D). These negative features vanish very quickly in the presence of decoherence. In the experiment by Lee *et al.*, a quantum state similar to (C) and (D) was teleported and kept the negative values of the Wigner function. This result demonstrates an extraordinary degree of experimental control over such fragile quantum objects.

(see the figure, panel A). For a squeezed state, the peak is still Gaussian but now has two-fold symmetry. One variance, say along *P*, is smaller than the vacuum noise, while the other one is larger (see the figure, panel B). For all optics experiments done during the last century, $W(Q, P)$ was some kind of Gaussian and therefore looked like a "real" (positive) probability distribution.

More surprisingly, the number state, where the number of photons in a light pulse is well defined, has a $W(Q, P)$ function that is negative at the origin (see the figure, panel C). Negative values are allowed because true probabilities are obtained by integrating these distributions—the integral over *P* gives the true probability distribution of *Q*. The integral of $W(Q, P)$ over any component of the electric field is the probability distribution of its orthogonal component (these appear as "shadows" in the figure panels).

This shadow idea is behind the method used to obtain $W(Q, P)$ experimentally. Many projections are measured so that $W(Q, P)$ can be reconstructed by a process called quantum tomography. All of the states with negative Wigner functions are called "nonclassical," because their discrete or continuous properties (or both) are now mixed and are purely quantum features. Many states with negative Wigner functions have recently been realized experimentally, including number states with one (*7*) or two photons (*8*), photon-added states (*9*), and entangled states with negative Wigner functions (*10*). Of particular interest here are superpositions of coherent states with opposite phases, which are called Schrödinger's kittens (*11–13*) or Schrödinger's cats (*14*, *15*), depending on their size (see the figure, panel D).

Such highly quantum states are desirable for efficient quantum information processing tasks, such as entanglement distillation in quantum communication, or as logical gates for quantum computing. These tasks involve many operations and are quite vulnerable to decoherence—the degradation of entanglement by unwanted coupling to the environment. A natural question is how well highly quantum states can be controlled in a basic processing operation.

The quantum teleportation of a Schrödinger's-cat state by Lee *et al.* successfully combined many operations. They generated a highly entangled state—the resource for teleportation—and independently a Schrödinger's-kitten state, the one to be teleported. Then, after the appropriate steps including the destruction of the initial kitten, they "recreated" this kitten in another place, still with negative features in its Wigner function. These final negative features can only be observed if the quality of the teleportation is high enough. This quality is measured by a number, called the fidelity, which must be greater than 2/3 for the operation to be successful. This 2/3 value is the so-called no-cloning limit, which also ensures that no other copy of the initial state can remain at the end (*16*, *17*): The cat state must really be "erased" somewhere in order to be able to "reappear" elsewhere.

Overall, such an achievement is certainly very impressive, and it goes beyond pure experimental virtuosity. It shows that the controlled manipulation of quantum objects has progressed steadily and achieved objectives that seemed impossible just a few years ago, and that tools are now available to tackle more ambitious goals.

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10.1126/science.1204814