Quantum Nonlocality: How Does Nature Do It?

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of details on how this binding could result in inhibition of the phosphatase. By determining the crystal structures of members of the receptor family, with and without bound abscisic acid and phosphatase, high-definition structural images of the initial steps in abscisic acid action are now available.

Collectively, the five studies (*1*–*5*) provide crystal structures of abscisic acid bound to its receptor, and four studies (*2*–*5*) go on to show the precise structural basis of the inhibition of the phosphatase active site. Dynamic measurements of nuclear magnetic resonance chemical shifts in solution corroborate the conclusions based on the crystal structures, in which the following scenario occurs: Abscisic acid binds to a pocket completely within a PYR-PYL homodimer, which then undergoes a conformational change resulting in a gate closing over this pocket, and a latch forming on the gate. This results in the tight binding of the hormone, which simultaneously exposes surfaces on the PYL protein that interact with the phosphatase and weaken the PYR-PYL dimer interface. The separation of PYR-PYL into monomers and interaction of these newly formed surfaces with the phosphatase active site function like a tightly bound competitive inhibitor. Removal of abscisic acid reverses the process, and the phosphatase is returned to its active state. This model is further substantiated by a large number of mutational studies, both in vitro with purified recombinant proteins and in transgenic plants and plant extracts.

So, is this model valid, and is there more to discover? Although it is clear that the details of abscisic acid binding to PYL proteins and the changes that result in binding to, and inhibition of, the phosphatase are nicely worked out, many questions remain. It is not clear whether all of the PYR and PYL proteins bind to abscisic acid, and why there are so many receptors. Are these hormone receptors widely expressed among plants? Whether these proteins have different tissue specificities or unique functionalizations, such as having differing affinities for abscisic acid or the phosphatase targets, needs to be determined. Further, what are all of the immediate substrates and/or binding partners for the phosphatase in plant cells? Data indicate that the phosphatase interacts with one or more protein kinases early in the abscisic acid signaling cascade. This creates the possibility that the time course and number of changes in the phosphorylation status of downstream proteins could be very complex because both sides of the amplification mechanism—adding and removing phosphates (by kinases and phosphatases, respectively)—might be involved at almost the same time. It is fascinating that whereas more than a thousand protein kinases genes are encoded within the plant genome, there are many fewer phosphatase genes. Furthermore, up to now, naturally occurring hormones seem to act directly on kinases, and it is the kinases that have been heralded as the central players of regulatory action and specificity, as shown mainly from work done in animals. It appears that abscisic acid is an example of a naturally occurring hormone having a protein phosphatase as part of its receptor action, rather than acting directly through a kinase. It will be interesting to note whether other eukaryotes are using similar mechanisms.

It is heartening that despite a poor start in the receptor characterization field, the START proteins turn out to be the key to abscisic acid action. The structural studies help explain how plants outsmart their adversaries and outlast poor environmental conditions, by going to sleep.

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PHYSICS

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Measurements of correlations between spatially separated systems provide insights into the conceptual foundations of quantum physics.

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From early childhood we know that to interact with an object, we have either to go to it or to throw something at it. Yet, contrary to all our daily experience, there are spatially separated quantum systems that exhibit nonlocal correlations. Exploring how nature performs its trick of quantum nonlocality (*1*) has led to new experiments that provide a deeper understanding of the tension between quantum physics and relativity and to proposals for disruptive technologies.

Consider two spatially separated quantum systems, one controlled by Alice, the other by Bob. They may perform some measurements on their respective systems and collect the results. After amassing probability distributions associated with their experiments, comparison of results can then tell them about any correlation between the experiments. It is establishing the structure of the correlations that distinguishes local from nonlocal. However, correlations are everywhere. For example, consider two cups of the same color, either both red or both green, one in Alice's and one in Bob's hands. If they look at the color of their cups, Alice's and Bob's results are correlated. In this classic example, the correlation is obvious. Alice and Bob had only partial information: They knew that both had the same color, but not which color. The quantum situation is profoundly different. Quantum theory claims that a pure state provides a complete description of the two systems. It was the development of this idea that led Einstein, Podolsky, and Rosen (*2*) to believe that quantum theory was incomplete, in the same sense that it could not provide the "which color" answer.

What can correlations tell you about nonlocality? In 1964, John Bell introduced a logical formulation, the now-famous Bell's inequality, which provided a refutable test for correlations being local or nonlocal. If the inequality was satisfied, then the correlations must be local. A violation of Bell's inequality not only tells us something about quantum physics, but more impressively, tells us that some spatially separated systems exhibit non-

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Under test. Tests of Bell inequality exploiting Earth's 24-hour rotation, setting stringent lower bounds on any hypothetical faster-than-light influence that could have explained the observed nonlocal correlations.

local correlations. This must be true for any future theory that is put forward as a complete quantum theory. Consequently, it is nature herself that is nonlocal.

There remains much uneasiness with nonlocality (*3*, *4*). A part of that comes from a confusion between nonlocal correlations and nonlocal signaling, whereby the possibility to signal at arbitrarily fast speeds is a clear contradiction to relativity. However, it is important to state that the nonlocal correlations of quantum physics are nonsignaling. That is, they do not communicate information. This should remove some of the uneasiness. Furthermore, in a nonsignaling world, correlations can be nonlocal only if the measurement results were not predetermined. Indeed, if the results were predetermined (and accessible with future theories and technologies), then one could exploit nonlocal correlations to signal. This fact has recently been used to produce bit strings with proven randomness (*5*). This is fascinating because it places quantum nonlocality no longer at the center of a debate full of prejudice, but as a resource for future quantum technologies.

The pioneering experiment by Clauser and Aspect probing the Bell test (*6*) suffered from a few loopholes, but these have since been separately closed (*7*, *8*). Still, correlations cry out for explanations, as emphasized by Bell. When confronted with nonlocal correlations, one feels that the two systems somehow influence each other (e.g., Einstein's famous spooky action at a distance). This is also the way textbooks describe the process: A first measurement triggers a collapse of the entire state function, hence modifying the state at the distant side. In recent years these intuitions have been taken seriously, leading to new experimental tests. If there is an influence from Alice to Bob, it must propagate faster than light, as existing experiments have already demonstrated violation of Bell's inequality between space-like separated regions (*9*). But a faster-than-light speed can only be defined with respect to a hypothetical universal privileged reference frame. The basic idea is that if correlations are due to some "hidden influence" that propagates at finite speed, then, if the two measurements are sufficiently well synchronized, the influence doesn't arrive on time and one shouldn't observe nonlocal correlations. There remains the problem, however, that one doesn't know a priori the privileged frame in which one should synchronize the measurements. This difficulty was recently circumvented by taking advantage of Earth's 24-hour rotation, thus setting stringent lower bounds on the speed of these hypothetical influences (see the figure) (*10*). Hence, nonlocal correlations happen without one system influencing the other. In another set of experiments the two observers, Alice and Bob, were set in motion in opposite directions in such a way that in their own inertial reference frame each of them felt that they had performed their measurement first and could thus not be influenced by their partner (*11*, *12*). Hence, quantum correlations happen without any time-ordering.

All of today's experimental evidence points to the conclusion that nature is nonlocal. This has implications both for our worldview and for future technologies. Quantum key distribution (QKD) is the most advanced application of quantum information science. Today's commercial QKD systems rely on sound principles, but their implementation has to be thoroughly tested to check for unwanted side channels that an adversary could exploit. For example, the photons emitted by Alice could, in addition to carrying a quantum bit encoded in its polarization state, also carry redundant information unwittingly encoded in the timing of the photons, or in their spectra. This is possible because today's QKD systems do not rely on nonlocal correlations. If they did, the mere fact that the correlations between the data collected by Alice and Bob violate Bell's inequality would suffice to guarantee the absence of any side channel. This was the intuition of Ekert in 1991 (*13*) but was proven only recently (*14*, *15*). The consequence (*16*) is that it will be possible to buy cryptography systems from one's adversary as the observation of nonlocal correlations will guarantee the proper functioning of the system.

In modern quantum physics, entanglement is fundamental; furthermore, space is irrelevant—at least in quantum information science, space plays no central role and time is a mere discrete clock parameter. In relativity, space-time is fundamental and there is no place for nonlocal correlations. To put the tension in other words: No story in space-time can tell us how nonlocal correlations happen; hence, nonlocal quantum correlations seem to emerge, somehow, from outside space-time.

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