ELEMENTS

QUANTUM THEORY BY STARLIGHT

By David Kaiser February 7, 2017

In parsing the strange dance of subatomic particles, it can be helpful to think of them as twins.

The headquarters of the National Bank of Austria, in central Vienna, are exceptionally secure. During the week, in the basement of the building, employees perform quality-control tests on huge stacks of euros. One night last spring, however, part of the bank was given over to a different sort of testing. A group of young physicists, with temporary I.D. badges and sensitive electronics in tow, were allowed up to the top floor, where they assembled a pair of telescopes. One they aimed skyward, at a distant star in the Milky Way. The other they pointed toward the city, searching for a laser beam shot from a rooftop several blocks away. For all the astronomical equipment, though, their real quarry was a good deal smaller. They were there to conduct a new test of quantum theory, the branch of physics that seeks to explain reality at the atomic scale.

It is difficult to overstate the weirdness of quantum physics. Even Albert Einstein and Erwin Schrödinger, both major architects of the theory, ultimately found it too outlandish to be wholly true. Throughout the summer of 1935, they aired their frustrations in a series of letters. For one thing, unlike Newtonian physics and Einstein's relativity, which elegantly explained the behavior of everything from the fall of apples to the motion of galaxies, quantum theory offered only probabilities for various outcomes, not rock-solid predictions. It was an "epistemology-soaked orgy," Einstein wrote, treating objects in the real world as mere puffs of possibility—both there and not there, or, in the case of Schrödinger's famous imaginary cat, both alive and dead. Strangest of all was what Schrödinger dubbed "entanglement." In certain situations, the equations of quantum theory implied that one subatomic particle's behavior was bound up with another's, even if the second particle was across the room, or on the other side of the planet, or in the Andromeda galaxy. They couldn't be communicating, exactly, since the effect seemed to be instantaneous, and Einstein had already demonstrated that nothing could travel faster than light. In a letter to a friend, he dismissed entanglement as "spooky actions at a distance"—

more ghost story than respectable science. But how to account for the equations?

Physicists often invoke twins when trying to articulate the more fantastical elements of their theories. Einstein's relativity, for instance, introduced the so-called twin paradox, which illustrates how a rapid journey through space and time can make one woman age more slowly than her twin. (Schrödinger's interest in twins was rather less academic. His exploits with the Junger sisters, who were half his age, compelled his biographer to save a spot in the index for "Lolita complex.") I am a physicist, and my wife and I actually have twins, so I find it particularly helpful to think about them when trying to parse the strange dance of entanglement.

Let us call our quantum twins Ellie and Toby. Imagine that, at the same instant, Ellie walks into a restaurant in Cambridge, Massachusetts, and Toby walks into a restaurant in Cambridge, England. They ponder the menus, make their selections, and enjoy their meals. Afterward, their waiters come by to offer dessert. Ellie is given the choice between a brownie and a cookie. She has no real preference, being a fan of both, so she chooses one seemingly at random. Toby, who shares his sister's catholic attitude toward sweets, does the same. Both siblings like their restaurants so much that they return the following week. This time, when their meals are over, the waiters offer ice cream or frozen yogurt. Again the twins are delighted—so many great options!—and again they choose at random.

In the ensuing months, Ellie and Toby return to the restaurants often, alternating aimlessly between cookies or brownies and ice cream or frozen yogurt. But when they get together for Thanksgiving, looking rather

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plumper than last year, they compare notes and find a striking pattern in their selections. It turns out that when both the American and British waiters offered baked goods, the twins usually ordered the same thing—a brownie or a cookie for each. When the offers were different, Toby tended to order ice cream when Ellie ordered brownies, and vice versa. For some reason, though, when they were both offered frozen desserts, they tended to make opposite selections—ice cream for one, frozen yogurt for the other. Toby's chances of ordering ice cream seemed to depend on what Ellie ordered, an ocean away. Spooky, indeed.

Einstein believed that particles have definite properties of their own, independent of what we choose to measure, and that local actions produce only local effects—that what Toby orders has no bearing on what Ellie orders. In 1964, the Irish physicist John

Bell identified the statistical threshold between Einstein's world and the quantum world. If Einstein was right, then the outcomes of measurements on pairs of particles should line up only so often; there should be a strict limit on how frequently Toby's and Ellie's dessert orders are correlated. But if he was wrong, then the correlations should occur significantly more often. For the past four decades, scientists have tested the boundaries of Bell's theorem. In place of Ellie and Toby, they have used specially prepared pairs of particles, such as photons of light. In place of friendly waiters recording dessert orders, they have used instruments that can measure some physical property, such as polarization—whether a photon's electric field oscillates along or at right angles to some direction in space. To date, every single published test has been consistent with quantum theory.

From the start, however,

physicists have recognized that their experiments are subject to various loopholes, circumstances that could, in principle, account for the observed results even if quantum theory were wrong and entanglement merely a chimera. One loophole, known as locality, concerns information flow: could a particle on one side of the experiment, or the instrument measuring it, have sent some kind of message to the other side before the second measurement was completed? Another loophole concerns statistics: what if the particles that were measured somehow represented a biased sample, a few spooky dessert orders amid thousands of unseen boring ones? Physicists have found clever ways of closing one or the other of these loopholes over the years, and in 2015, in a beautiful experiment out of the Netherlands, one group managed to close both at once. But there is a third major loophole, one that Bell overlooked in his original analysis. Known as the freedom-of-choice loophole, it concerns whether some event in the past could have nudged both the choice of measurements to be performed and the behavior of the entangled particles—in our analogy, the desserts being offered and the selections that Ellie and Toby made. Where the locality loophole imagines Ellie and Toby, or their waiters, communicating with each other, the freedom-of-choice loophole supposes that some third party could have rigged things without any of them noticing. It was this loophole that my colleagues and I recently set out to address.

We performed our experiment last April, spread out in three locations across Schrödinger's native Vienna. A laser in Anton Zeilinger's laboratory at the Institute for Quantum Optics and Quantum Information supplied our entangled photons. About three-quarters of a mile to the north, Thomas Scheidl and his colleagues set up two telescopes in a different university building. One was aimed at the institute, ready to receive the entangled photons, and one was pointed in the opposite direction, fixed on a star in the night sky. Several blocks south of the institute, at the National Bank of Austria, a second team, led by Johannes Handsteiner, had a comparable setup. Their second telescope, the one that wasn't looking at the institute, was turned to the south.

Our group's goal was to measure pairs of entangled particles while insuring that the type of measurement we performed on one had nothing to do with how we assessed the other. In short, we wanted to turn the universe into a pair of random-number generators. Handsteiner's target star was six hundred light-years from Earth, which meant that the light received by his telescope had been travelling for six hundred years. We selected the star carefully, such that the light it emitted at a particular moment all those centuries ago would reach Handsteiner's telescope first, before it could cover the extra distance to either Zeilinger's lab or the university. Scheidl's target star, meanwhile, was nearly two thousand light-years away. Both team's telescopes were equipped with special filters, which could distinguish extremely rapidly between photons that were more red or more blue than a particular reference wavelength. If Handsteiner's starlight in a given instant happened to be more red, then the instruments at his station would perform one type of measurement on the entangled photon, which was just then zipping through the night sky, en route from Zeilinger's laboratory. If Handsteiner's starlight happened instead to be blue, then the other type of measurement would be performed. The same went for Scheidl's station. The detector settings on each side changed every few millionths of a second, based on new observations of the stars.

With this arrangement, it was as if each time Ellie walked into the restaurant, her waiter offered her a dessert based on an event that had occurred several centuries earlier, trillions of miles from the Earth—which neither Ellie, nor Toby, nor Toby's waiter could have foreseen. Meanwhile, by placing Handsteiner's and Scheidl's stations relatively far apart, we were able to close the locality loophole even as we addressed the freedom-of-choice loophole. (Since we only detected a small fraction of all the entangled particles that were emitted from Zeilinger's lab, though, we had to assume that the photons we did measure represented a fair sample of the whole collection.) We conducted two experiments that night, aiming the stellar telescopes at one pair of stars for three minutes, then another pair for three more. In each case, we detected about a hundred thousand pairs of entangled photons. The results from each experiment showed beautiful agreement with the predictions from quantum theory, with correlations far exceeding what Bell's inequality would allow. Our results were published on Tuesday in the journal *Physical Review Letters*.

How might a devotee of Einstein's ideas respond? Perhaps our assumption of fair sampling was wrong, or perhaps some strange, unknown mechanism really did exploit the freedom-of-choice loophole, in effect alerting one receiving station of what was about to occur at the other. We can't rule out such a bizarre scenario, but we can strongly constrain it. In fact, our experiment represents an improvement by sixteen orders of magnitude—a factor of ten million billion—over previous efforts to address the freedom-of-choice loophole. In order to account for the results of our new experiment, the unknown mechanism would need to have been set in place before the emission of the starlight that Handsteiner's group observed, back when Joan of Arc's friends still called her Joanie.

Experiments like ours—and follow-up versions we plan to conduct, using larger telescopes to spy even fainter, more distant astronomical objects—harness some of the largest scales in nature to test its tiniest, and most fundamental, phenomena. Beyond that, our explorations could help shore up the security of next-generation devices, such as quantum-encryption schemes, which depend on entanglement to protect against hackers and eavesdroppers. But, for me, the biggest motivation remains exploring the strange mysteries of quantum theory. The world described by quantum mechanics is fundamentally, stubbornly different from the worlds of Newtonian physics or Einsteinian relativity. If Ellie's and Toby's dessert orders are going to keep lining up so spookily, I want to know why.

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