QUANTUM MECHANICS

'Spooky Action' Passes a Relativistic Test

Framed by physicists trying to catch them in a contradiction, entangled photons stick to their quantum story

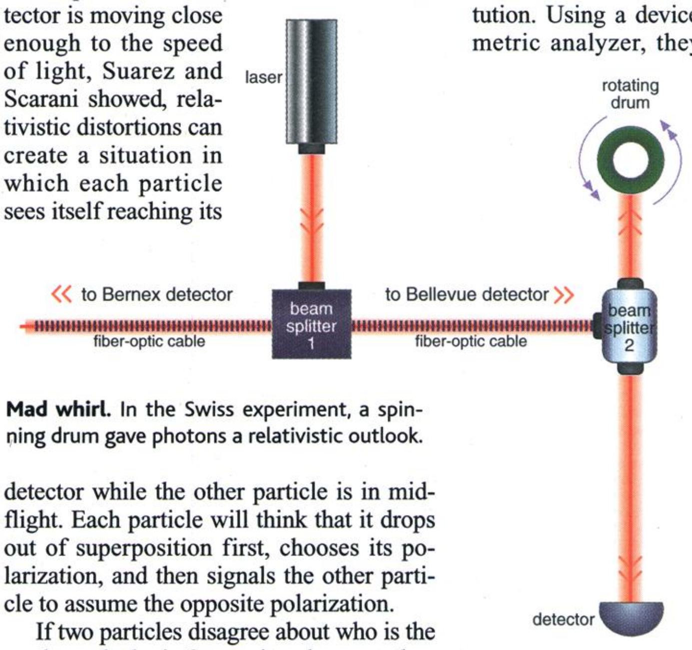
The most unnerving idea in quantum mechanics may be "spooky action at a distance"—the notion that certain particles can affect one another almost instantly across vast reaches of space. Einstein spent half his life wielding such so-called nonlocal effects against quantum theory, and other physicists have followed suit on paper and in the lab ever since. Recently in Geneva, that aspect of quantum surreality survived the most cunning trap so far, a series of experiments that pitted it against basic principles of Einstein's relativity. The results gave the most accurate estimate yet of how rapidly the "spooky action" might operate.

"I was excited to see that [the Geneva lab] had really done it," says quantum computer expert Gilles Brassard, a professor at the University of Montreal. "Of course, if the outcome had been the other way, and the correlation disappeared, it would have been a Nobel Prize experiment."

The Swiss team probed an intimate linkage between quantum particles known as entanglement. To entangle photons, for example, a scientist might set up a device that creates them in pairs with opposite, but unknown, polarizations. If one photon is polarized vertically, then the other must be polarized horizontally, and vice versa. In the quantum world, however, a photon can exist in an undecided "superposition" of horizontal and vertical states, declaring its polarization only when somebody measures it. If one of the entangled photons then becomes (say) horizontally polarized upon being measured, the other photon must simultaneously decide to become vertically polarized—even if it is a billion light-years away. Somehow the first photon has sent a signal to its distant twin.

Such linked particles are known as EPR pairs, after Einstein and two collaborators who used them in 1935 to attack quantum theory on the grounds that they violated the relativistic ban on faster-than-light communication. (Physicists later showed that there is no violation, because the "quantum information" EPR pairs carry can't be harnessed to send useful messages.) In 1996, however, two Swiss physicists, Antoine Suarez and Valerio Scarani, proposed that EPR pairs run afoul of another cornerstone of Einstein's theory, the relativity of time.

Einstein showed that the flow of time, and even the order of events, depends on how fast an observer is moving. Suarez and Scarani dreamed up a thought experiment in which an experimenter creates an entangled pair of photons and fires each toward a different particle detector. If both detectors are standing still, it is easy to tell which particle arrives first. But if one detector is moving close enough to the speed of light, Suarez and Scarani showed, relativistic distortions can create a situation in which each particle sees itself reaching its detector while the other particle is in midflight. Each particle will think that it drops out of superposition first, chooses its polarization, and then signals the other particle to assume the opposite polarization.



Mad whirl. In the Swiss experiment, a spinning drum gave photons a relativistic outlook.

If two particles disagree about who is the sender and who is the receiver, how can they be communicating? They can't, Suarez and Scarani said. Contrary to the standard interpretations of quantum mechanics (which require that the particles somehow stay entangled even in such a "before-before" situation), entanglement will break down, and each particle's fate will become independent of the other's.

The Geneva scientists put the rival outcomes to an experimental test. In their lab, they shot a laser beam into a crystal made of potassium, niobium, and oxygen. On absorbing a photon from the laser, the crystal spat out two entangled photons, which sped down different fiber-optic cables to detectors in the nearby villages of Bernex and Bellevue, 10.6 kilometers apart. What entangled the photon pairs in this case was not polarization, but energy and timing, which are tied together quantum mechanically. "Each of the photons has an uncertain energy, but the sum of the energy of the two photons is very well defined," says Nicolas Gisin, a member of the team.

By measuring with incredible precision (about 5 picoseconds) when various photons in the beams reached the detectors, the scientists could tell which photons had been entangled. Almost incidentally, they determined that quantum information must travel faster than 10^7 times the speed of light. Otherwise, the correlation between entangled particles would have broken down.

Then the fun began. To create a relativistic "before-before" anomaly, the scientists in effect cranked the Bellevue detector up to relativistic speeds by making it spin in place at 10,000 revolutions per minute. An ordinary measuring device would have flown apart in seconds, so the Geneva team made a clever—and controversial—substitution. Using a device called an interferometric analyzer, they split the Bellevue beam again, sending the photon down two paths simultaneously (as wave particles are wont to do). One path led to a dummy detector made of a sheet of black paper wrapped around a whirling drum, and the other to a stationary detector. A nonclick at the stationary detector meant that the photon had struck the black paper. Thus, Gisin says, "there is not a real difference between an absorbing black surface and a detector."

Because that surface was spinning away from the crystal that entangled the photons in the first place, its motion created a relativistic before-before situation. Photons in Bellevue were convinced they had arrived before their EPR partners in Bernex, and vice versa. Then negative readings at the stationary detector told the experimenters exactly which pairs of photons had been entangled. "The 'no click' on the detector—that is the only information we need," Gisin says.

Gisin's team measured the correlations between the Bernex and Bellevue photons, both when the dummy detector was stationary and when it was spinning. The result: Entangled photons stayed entangled, even if each thought it had struck a detector first. Einstein's frames had no effect on spooky action.

Other scientists say the results are impressive but not quite airtight. "They are very beautiful from an experimental point of view, but there are too many assumptions," says Anton Zeilinger, a physicist at the University of Innsbruck in Austria. For example, no one is sure that a moving piece of paper is, in fact, as good as a moving detector.

The experimenters also assumed, as most physicists do, that the photon chooses its quantum state at the moment it strikes a detector. In some formulations of quantum mechanics, however, the photon makes its choice at other points in the experiment—even as late as the time when a conscious being finally looks at the data on the computer. Zeilinger hopes to narrow the possibilities, perhaps by inserting rapid, randomly activated switches into the experimental setup.

However they interpret the results, scientists agree that the Geneva experiments are a technological feat. "This is, in a certain sense, a new line in experimental work," says Suarez. "You are putting quantum mechanics in a relativistic frame."

—CHARLES SEIFE

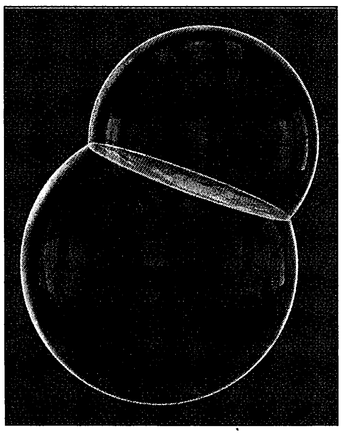
MATHEMATICS

Rounding Out Solutions to Three Conjectures

Three long-standing puzzles involving spherical bodies—the configuration of double bubbles, stable orbits of three stars, and random packing of spheres in a box—have all been solved

Why Double Bubbles Form the Way They Do

Need to entertain a child? Try blowing soap bubbles. Need to keep a mathematician busy? Just ask why bubbles take the shapes they do. Individual soap bubbles, of course, are spherical, and for a very simple reason: Among all surfaces that enclose a given volume, the sphere has the least area (and in the grand scheme of things, nature inclines toward such minima). On the other hand, when two soap bubbles come together, they form a "double bubble," a simple complex of three partial spheres: two on the outside, with the third serving as a wall between the two compartments. Scientists have long considered it obvious that double bubbles behave this way for the same minimum-seeking reason—because no other shape encloses two given volumes with less total surface area. But mathematicians have countered with their usual vexing question: Where's the proof?



Soap solution. Mathematicians prove that nature's way of forming double bubbles is best.

Now they have it. An international team of four mathematicians has announced a proof of the double bubble conjecture. By honing a new technique for analyzing the stability of competing shapes, Michael Hutchings of Stanford University, Frank Morgan of Williams College in Williamstown, Massachusetts, and Manuel Ritoré and Antonio Ros at the University of Granada have shown that only the standard shape is truly minimal—any other, supposedly area-minimizing shape can be ever so slightly twisted into a shape with even less area, a contradiction which rules out these other candidates.

What other shape could two bubbles possibly take? One candidate—or class of candidates—has one bubble wrapped around the other like an inner tube. But it could be even worse: Mathematically, there's no objection to splitting a volume into two separate pieces, so it's possible that siphoning off a bit of the central volume and reinstalling it as a "belt" around the inner tube would actually reduce the total surface area. And conceivably, then, siphoning a bit of the inner tube and placing it as a band around the belt would lead to smaller area yet, and so forth. There's not even any obvious reason that the true, area-minimizing double bubble can't have "empty chambers"—enclosed regions that don't belong to either volume.

Just about the only thing that's (relatively) easy to prove is that the solution must have an axis of symmetry—in other words, it can't have lopsided bulges. Hutchings took the first big step toward ruling out the more bizarre possibilities in the early 1990s. He ruled out empty chambers and showed that the larger volume must be a single piece. Besides the standard double bubble, his results limited the possible solutions to ones consisting of a large inner tube around a small central region, perhaps with a set of one or more belts circling the outside. Hutchings also found formulas that provide bounds on the number of belts, as a function of the ratio of the two volumes. In particular, if the two volumes are equal, or even nearly equal, there can be no belts, so the only alternative is a single inner tube around a central region.

Based on Hutchings's work, in 1995 Joel Hass of the University of California (UC), Davis, and Roger Schlafly, now at UC Santa Cruz, proved the double bubble conjecture for the equal-volume case. Their proof used computer calculations to show that any inner tube arrangement can be replaced by another with smaller area. "Ours was a comparison method," Hass explains. He and Schlafly found they could extend their results for volume ratios up to around 7:1, but beyond that the possible configurations to be ruled out became too complicated.

Surprisingly, the general proof requires no computers, just pencil and paper. The key idea consists of finding an "axis of instability" for each inner tube arrangement. Twisting the two volumes around this axis—with a motion rather like wringing out a washcloth—leads to a decrease in surface area, contradicting the shape's ostensible minimality. "We always thought that these remaining cases were unstable," Morgan says. The proof confirms their suspicions, although it leaves open the possibility that some nonminimizing configuration could also be stable. The twisting argument is new and a bit subtle, Morgan notes. The hardest part is figuring out where to position the axis of instability so that the twisting procedure wouldn't change the volumes of the two regions as well as the surface area. "For a while, it was hard to frame the right questions, especially in Spanish."

Although the proof is only now being announced, the main results were established last spring, when Morgan visited Granada during a sabbatical. Since then, a group of undergraduates in a summer research program at Williams College has extended the results to analogs of the double bubble conjecture in higher dimensions. (The two-dimensional double bubble conjecture was proved by an earlier group of undergraduates in 1990.) Ben Reichardt of Stanford, Yuan Lai of the Massachusetts Institute of Technology, and Cory Heilmann and Anita Spielman of Williams College have shown that an axis

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