Quantum entanglement reaches new heights

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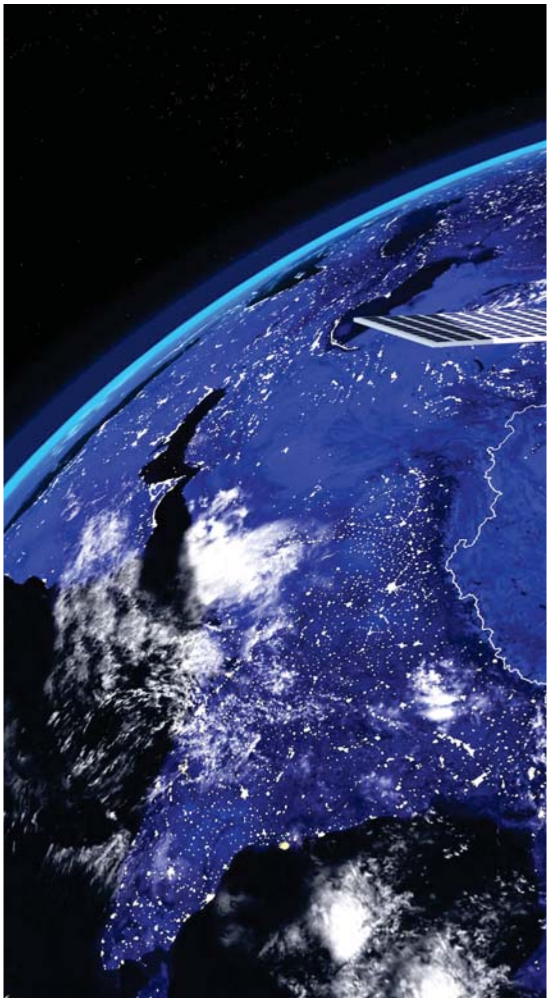
The satellite-based distribution of entangled photons to cities 1200 km apart bolsters prospects for a global quantum communication network.



Jian-Wei Pan nearly wept as he watched a Long March rocket lift off from China's Jiuquan Satellite Launch Center in the Gobi Desert in August 2016. The rocket carried the *Quantum Science Satellite*, which Pan and coworkers at the University of Science and Technology of China (USTC) had spent five years building and refining. He had spent twice that long lobbying to get the $100 million project funded. To see it finally off the ground, he says, "was truly a relief."

The satellite, nicknamed *Micius* after the ancient Chinese philosopher, was to be the hub of an experimental quantum communications network. To start, it would take turns beaming pairs of polarization-entangled photons from its low-Earth, Sun-synchronous orbit to four ground stations throughout China (see figure 1). Such transmissions would allow two stations to secretly exchange information: Quantum mechanics posits that a measurement on one of a pair of entangled photons instantly determines the state of the other, no matter how distant. Because a third party can't tamper with the photons without destroying their entanglement, there's no way to eavesdrop undetected. (See the article by Daniel Gottesman and Hoi-Kwong Lo, PHYSICS TODAY, November 2000, page 22.)

Nothing in quantum mechanics limits the distance over which two photons can be entangled. But the farther they travel from each other, the more likely are their fragile quantum states to be disturbed by the environment along the way. When Pan began pondering a quantum network in the 1990s, entanglement had yet to be demonstrated beyond length scales of a few meters. To link cities and countries, it would have to be implemented at distances millions of times larger.

Now, a year after *Micius*'s launch, Pan and his coworkers report a milestone in their quest to build a quantum communications network: *Micius* has successfully distributed pairs of entangled photons between the Chinese cities of Delingha, on the Tibetan Plateau, and Lijiang, 1200 km to the south.[1] Never has the spooky action of quantum mechanics been observed at so great a distance.

"A crazy idea"

Micius has roots in work that Pan did as a graduate student two decades ago at the University of Innsbruck in Austria. There he, his adviser Anton Zeilinger, and their coworkers demonstrated a scheme for quantum teleportation: By measuring one of two entangled photons jointly with a third photon in an arbitrary quantum state, they could instantly project that state onto the other entangled photon.[2]

Intrigued by the potential implications for quantum communication, both Pan and Zeilinger began thinking about ways to orchestrate long-distance entanglement. In 2001, when Pan took a faculty position at USTC in Hefei, he allocated half of his CNY2.4 million ($290 000) in startup funds to pursue satellite-based quantum communication. "People thought it was a crazy idea," he recalls, "because it was already very challenging to do the sophisticated quantum optics experiments on a well-shielded optical table. How could you do them in space?"

Pan faced two main obstacles. One was the inherent difficulty of coherently transmitting photons over large distances. Although optical fibers can be used to distribute entangled photons between, say, distant buildings on a campus,[3] a photon would stand a negligible chance of surviving a trip longer than a few kilometers. Pan would instead beam light directly through the air. Inevitably, some photons are still lost to scattering and absorption. But if the beam and detector are well aligned, those losses are far smaller than in optical fibers.

In a 2005 ground test, Pan and coworkers successfully beamed entangled photons from the summit of Dashu Mountain to two sites more than 10 km apart in the city of Hefei below.[4] They later duplicated the feat over distances of 16 km along the Great Wall and 100 km across China's Qinghai Lake. By 2012 the group was regularly distributing entanglement over distances greater than the 10 km effective thickness of Earth's atmosphere. So was Zeilinger, who had been pursuing similar research in Austria.[5] There was little reason to doubt that entangled photons could survive a journey from space.

Generating the photons, however, was another matter. A common tactic is to use a nonlinear crystal to convert a pump photon into two photons of half the frequency—a process known as spontaneous parametric down conversion. If the phases and spatial modes of those photons overlap, the photons can become entangled.

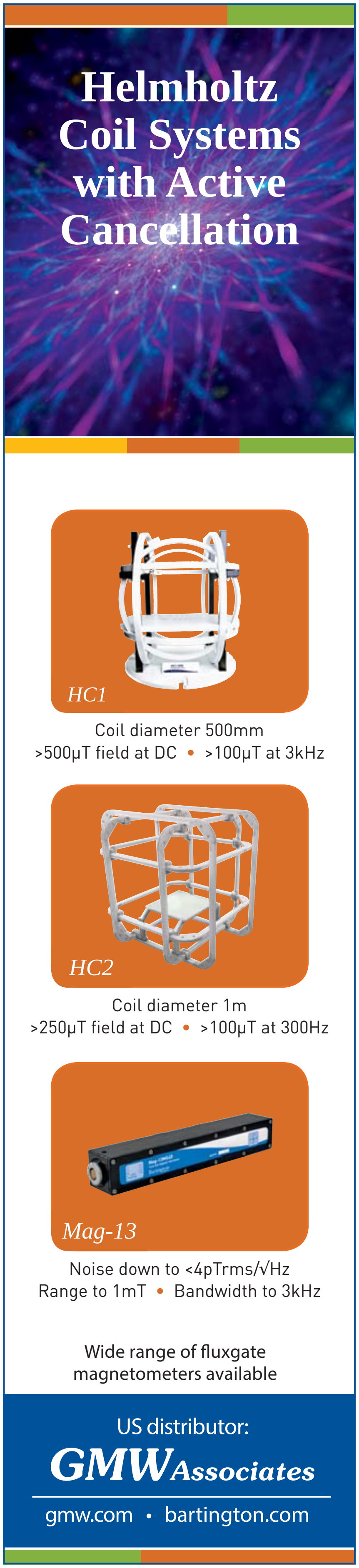
FIGURE 1. THE *QUANTUM SCIENCE SATELLITE*, nicknamed *Micius*, successfully beamed polarization-entangled photons from low-Earth orbit to two ground stations 1200 km apart in Delingha and Lijiang, China. Such satellite-based entanglement distribution could provide the basis for a highly secure quantum communications network. (Illustration courtesy of Jian-Wei Pan.)

The rates of entangled-pair generation tend to be low, but in ground tests Pan and his colleagues could compensate by pumping their crystal generously; at Qinghai Lake, they used a 1.3 W pump laser to generate 40 000 pairs of entangled photons per second. To produce a suitably bright photon beam using the limited power available on a satellite, they'd need a more efficient scheme.

The group ultimately adopted a strategy developed by Franco Wong's group at MIT, in which the nonlinear crystal is placed inside an interferometer to improve the overlap of photons' spatial modes and phases.[6] Pumped by a 30 mW laser, the source could generate nearly six million pairs of entangled photons per second. Moreover, the key ingredient, an interferometer known as a Sagnac loop, is insensitive to vibrational, thermal, and electromagnetic disturbances. In other words, it's perfectly suited for the rigors of space travel.

The entangled web

Every night at around 1:30am local time, *Micius* hurtles into view of Delingha and then Lijiang. For roughly four and a half minutes, it's visible from both cities. During that brief window, it sends polarization-entangled IR photons to the two sites' ground receivers, 1 m telescopes coupled to single-photon detectors. A 100 kHz pulsed laser beam, emitted alongside the entangled photons, provides a time stamp: Tiny phase fluctuations known as jitter allow ground-based observers to determine whether two photons were emitted simultaneously. Red laser beacons emitted from each ground station and green ones emitted from the satellite help the satellite and receivers locate one another. The



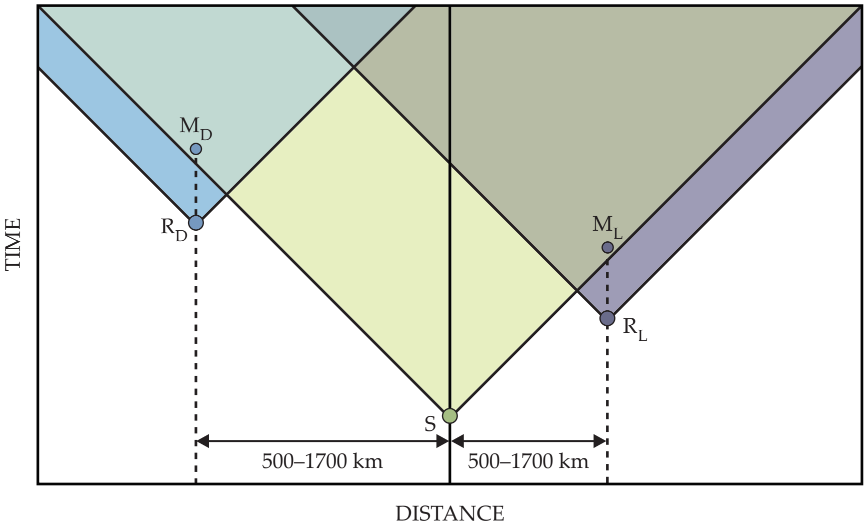


FIGURE 2. IN A BELL TEST performed with detectors in Delingha and Lijiang, China, two polarization-entangled photons generated on a satellite at S travel 500–1700 km before being measured at M_D and M_L, respectively. Polarization measurement angles are chosen randomly at R_D and R_L, microseconds before the photons' arrivals. Because R_D and R_L lie outside the light cone of S, information generated during the entanglement process can't affect the choice of measurement angle. Because R_D and M_D lie outside the light cones of R_L and M_L and vice versa, the angle and outcome of one measurement can't affect those of the other, except through the action of quantum entanglement. (Adapted from ref. 1.)

feedback-controlled system is so precise that the satellite's aim is limited only by the diffraction of the photon beams, which broaden to spots 5–15 m in diameter by the time they reach the ground.

Due to diffraction, atmospheric scattering and absorption, and the occasional pointing error, only about one in six million photon pairs—or one pair per second—reaches both ground stations. Still, it took only four minutes of effective observation time for Pan and his coworkers to begin to see correlations among the photon pairs: A vertically polarized photon at one site almost always coincided with a horizontally polarized one at the other.

To show, however, that the photons were not merely correlated but quantum entangled, Pan and his colleagues had to perform what's known as a Bell's inequalities test. (See PHYSICS TODAY, January 2016, page 14.) In the version they implemented, a photon arriving at Delingha is measured by a polarizer oriented at one of two angles, θ_D or θ'_D, whereas its partner at Lijiang is measured at one of two different angles, θ_L or θ'_L. The measurement angle is randomly selected just a few microseconds before the photon arrives, as illustrated in figure 2, so that no information generated during the entanglement can influence the choice and no choice made at one detector can influence the measurement at the other.

Under that protocol, Bell's theorem predicts a quantitative difference between the correlations produced by quantum entanglement and those that can be produced by classical phenomena. After some 20 minutes of observation, spread over several nights, Pan and his colleagues could conclude with confidence that their correlations couldn't possibly be classical.

The result completes the first of three experiments planned for *Micius*. Next, Pan and his colleagues hope to use the satellite to distribute encryption keys and, ultimately, perform quantum teleportation. They also plan to grow their fledgling network: In a collaboration involving Zeilinger, *Micius* may soon begin transmitting to a ground station in Vienna.

Stumbling blocks still litter the road to a practical quantum communications network. The current transmission rate of 1 bit per second is unrealistically small for most applications, and Pan and his colleagues will need to substantially improve their noise-filtering schemes if they hope to detect entangled photons during the daytime.

Still, *Micius* presents immediate opportunities to explore fundamental physics.

Pan is particularly keen to probe interactions between quantum mechanics and gravity. “We’ve established a quantum optics laboratory with an effective lab space of a million square kilometers,” he says. “We can experiment at distances and velocities that were inaccessible on the ground.”

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Quantum gases cooled to long-range antiferromagnetic order

The observation of a checkerboard pattern in a lattice of ultracold atoms is a sign of even more exciting experiments to come.

In the spring of 1986, Georg Bednorz and Alex Müller of IBM Zürich Research Laboratory discovered that a certain copper oxide ceramic became a superconductor at a temperature T_c of 30 K, some 10 K higher than any previously studied material. The finding was immediately recognized as a game changer: It won the pair a Nobel Prize the very next year (see PHYSICS TODAY, December 1987, page 17) and launched a frenzied new research field that quickly turned up other families of cuprates with critical temperatures well above 100 K.

Thirty years later, despite intense theoretical and experimental study, high-T_c superconductivity remains largely mysterious. It’s known that the superconductivity occurs in particular lattice planes and depends sensitively on the charge-carrier density, or doping, which can be controlled by tweaking the material composition. Still unknown are the mechanism by which electrons pair up to condense into a superfluid, why the normally insulating ceramics become superconducting at all, and how best to search for new superconductors with even higher T_c, possibly as high as room temperature.

New insights may be on their way from an unlikely source. Cold-atom researchers are hoping to capture the physics of high-T_c superconductors by mimicking the electrons with neutral atoms in an array of optical traps. If they succeed, they’ll be able to study the inner workings of the superconducting and related phases in a way that’s otherwise inaccessible to either theory or experiment. Trapped atoms can be interrogated and manipulated one by one. Electrons in a solid can’t.

In realizing that hope, the main challenge is temperature. Though at just tens of nanokelvin they are ultracold by any absolute standards, state-of-the-art atomic experiments act like solids with temperatures of hundreds of kelvin, far from the most enticing parts of the cuprate phase diagram. Now Harvard University’s Markus Greiner and colleagues have taken a step into uncharted territory.[1] They’ve cooled their system of lithium-6 atoms far enough to see antiferromagnetic order—the checkerboard pattern in figure 1—across their entire 80-site two-dimensional lattice. “Interesting states like high-T_c superconductivity are often found in the vicinity of antiferromagnetism,” says Greiner. So although the experiments haven’t turned up any new physics just yet, it may not be long before they do.

Theory follows experiment

Although seemingly unrelated, solid-state and cold-atom systems are connected by the Hubbard model, which was proposed in 1963 as a stripped-down theoretical description of the electrons in a solid. (John Hubbard himself died in 1980, so he never had the chance to consider the model’s applicability to