THE QUANTUM SPACE RACE

Fierce rivals have joined forces in the race to teleport information to and from space.

BY ZEEYA MERALI

Three years ago, Jian-Wei Pan brought a bit of *Star Trek* to the Great Wall of China. From a site near the base of the wall in the hills north of Beijing, he and his team of physicists from the University of Science and Technology of China (USTC) in Hefei aimed a laser at a detector on a rooftop 16 kilometres away, then used the quantum properties of the laser's photons to 'teleport' information across the intervening space[1]. At the time, it was a world distance record for quantum teleportation, and a major step towards the team's ultimate aim of teleporting photons to a satellite.

If that goal is achieved, it will establish the first links of a 'quantum Internet' that harnesses the powers of subatomic physics to create a super-secure global communication network. It will confirm China's ascent in the field, from a bit-player a little more than a decade ago to a global powerhouse: in 2016, ahead of Europe and North America, China plans to launch a satellite dedicated to quantum-science experiments. It will offer physicists a new arena in which to test

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DANIEL PADRÓN

Experiments in the Canary Islands hold the distance record for quantum teleportation.

the foundations of quantum theory, and explore how they fit together with the general theory of relativity — Einstein's very different theory of space, time and gravity.

It will also mark the culmination of Pan's long, yet fiercely competitive, friendship with Anton Zeilinger, a physicist at the University of Vienna. Zeilinger was Pan's PhD adviser, then for seven years his rival in the long-distance quantum-teleportation race, and now his collaborator. Once the satellite launches, the two physicists plan to create the first intercontinental quantum-secured network, connecting Asia to Europe by satellite. "There's an old Chinese saying, 'He who teaches me for one day is my father for life,'" says Pan. "In scientific research, Zeilinger and I collaborate equally, but emotionally I always regard him as my respected elder."

FAST MOVER

Pan was only in his early thirties when he set up China's first lab for manipulating the quantum properties of photons in 2001, and when he proposed the satellite mission in 2003. And he was 41 in 2011, when he became the youngest researcher ever to be inducted into the Chinese Academy of Sciences. "He almost single-handedly pushed this project through and put China on the quantum map," says team member Yu-Ao Chen, also at the USTC.

Pan's drive dates back to his undergraduate years at the USTC in the late 1980s, when he first encountered the paradoxes at play in the atomic realm. Quantum objects can exist in a superposition of many states: a particle can spin both clockwise and anticlockwise at the same time, for instance, and it can simultaneously be both here and over there. This multiple personality is described mathematically by the particle's wavefunction, which gives the probability that it is in each of those states. Only when the particle's properties are measured does the wavefunction collapse, choosing a definite state in a single location. Crucially, there is no way, even in principle, to predict the result of a single experiment; the probabilities show up only as a statistical distribution and only when the experiment is repeated many times.

Things get even weirder when two or more particles are involved, thanks to the quantum property of entanglement. Multiple particles can be prepared in such a way that measurements on one are correlated with measurements made on the others, even if the particles are separated by huge distances — and even though the phenomenon of superposition demands that these properties cannot be fixed until the instant they are probed. It is as strange as a physicist in Beijing and another in Vienna flipping coins in unison, and finding that they always either both throw heads or both throw tails. "I was obsessed with these quantum paradoxes," says Pan. "They distracted me so much that I couldn't even study other things." He wanted to test the veracity of these almost inconceivable claims, but he could not find a suitable experimental quantum physics lab in China.

The natural progression for budding Chinese physicists in Pan's position was to study in the United States — so natural, in fact, that fellow students joked that their university's acronym, USTC, actually stood for 'United States Training Centre'. But Pan wanted to learn from a quantum experimental master. And for him, one physicist stood out: Zeilinger.

In 1989, Zeilinger had collaborated with physicists Daniel Greenberger, now at the City University of New York, and Michael Horne, now at Stonehill College in Easton, Massachusetts, on a key theorem governing the entanglement of three or more particles[2]. The work was a turning point for the field — and for Zeilinger. "At conferences, I realized that very important older physicists had started to regard me as the quantum expert," he says. By the mid-1990s, Zeilinger had set up his own quantum lab at the University of Innsbruck in Austria and needed a student to test some of his ideas. Pan seemed the perfect fit. So, in a rare move for a Chinese student, Pan relocated to Austria, beginning a relationship with Zeilinger that would see their careers develop in tandem over the next two decades.

Even as a graduate student, Pan had big ambitions for his home country. At their first meeting, Zeilinger asked Pan what his dream was. "To build in China a world-leading lab like yours," Pan replied. Zeilinger was impressed. "When he first came, he knew nothing about working in a lab, but he quickly picked up the rules of the game and was soon inventing his own experiments," he says. "I always knew he would have a wonderful career — but the incredible success that he has had, I don't think anyone could have foreseen. I am very proud of him."

While Pan was mastering his craft in Zeilinger's lab, physicists around the world were slowly embracing the notion that the esoteric quantum features that so enchanted Pan could be harnessed to create, say, ultra-powerful quantum computers. Standard computers chug slowly through information coded in binary digits — strings of zeros and ones. But as early as 1981, the physicist Richard Feynman had pointed out that quantum bits, known as 'qubits', need not be so encumbered. Because a qubit can simultaneously exist in superpositions of 0 and 1, it should be possible to build faster, more powerful quantum computers that would entangle multiple qubits together and perform certain calculations in parallel, and at breathtaking speed.

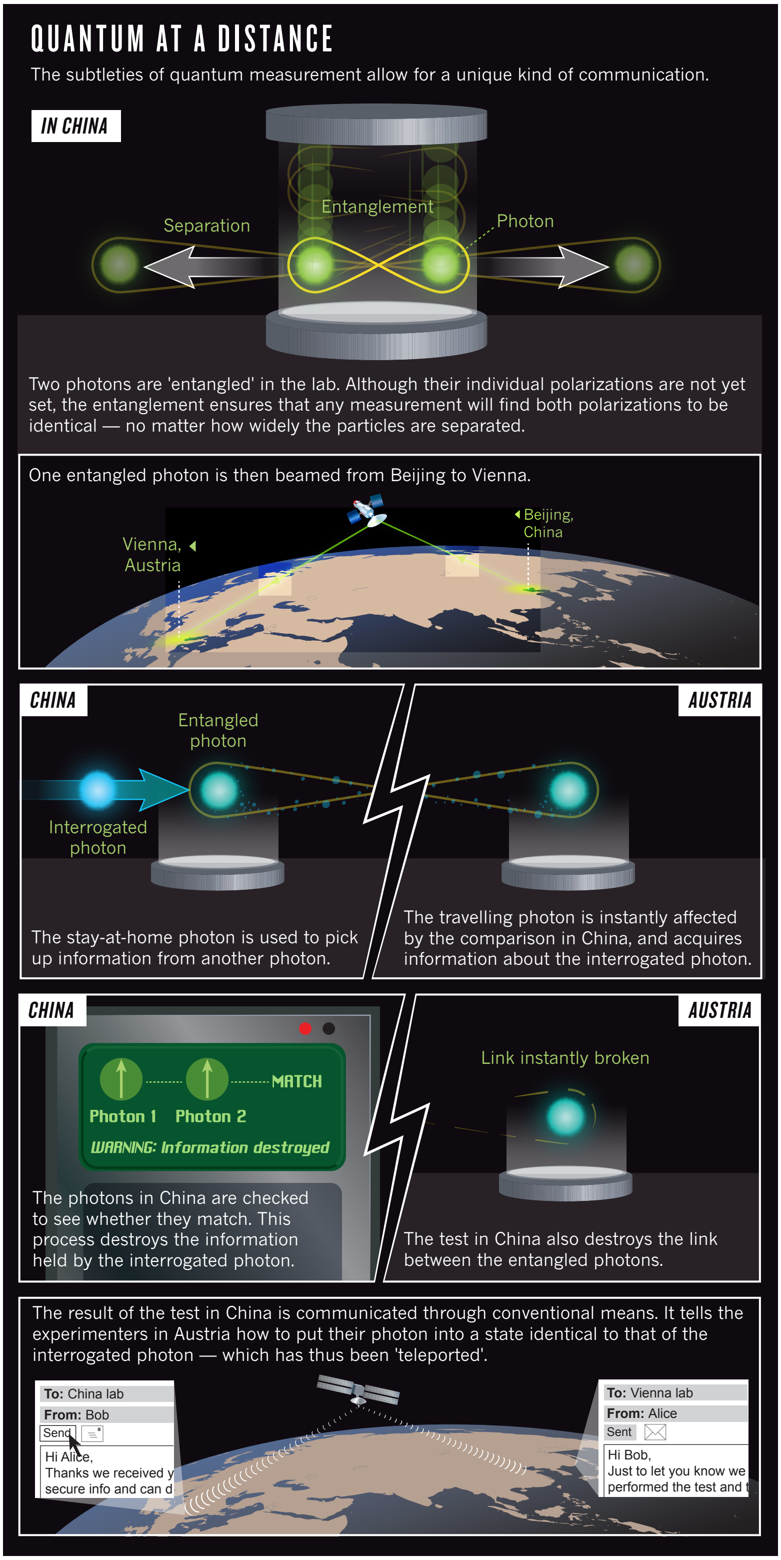
Another emerging idea was ultra-secure quantum encryption for applications such as bank transactions. The key idea is that measuring a quantum system irrevocably disrupts it. So two people, Alice and Bob, could generate and share a quantum key, safe in the knowledge that any meddling by an eavesdropper would leave a trace.

By the time Pan returned to China in 2001, the potential for quantum-based technologies was recognized enough to attract financial support from the Chinese Academy of Sciences and the National Natural Science Foundation of China. "The lucky thing was that in 2000 the economy of China started to grow, so the timing was suddenly right to do good science," Pan says. He plunged into building his dream lab.

Back in Austria, meanwhile, Zeilinger had moved to the University of Vienna, where he continued to set quantum records thanks to his penchant for thinking big. One of his most celebrated experiments showed that buckyballs, fullerene molecules containing 60 carbon atoms, can exhibit both wave and particle behaviour[3] — a peculiar quantum effect that many thought could not survive in such large molecules. "Everyone had been talking about maybe trying this experiment with small, diatomic molecules," recalls Zeilinger. "I said, 'no guys, don't just think of the next one or two steps ahead, think about how to make a huge unexpected leap beyond everyone's thinking'."

That was a lesson that Pan heeded well. Physicists around the world were beginning to imagine the futuristic quantum Internet, based on links between quantum computers that had yet to be built. At a time when most practitioners were still happy to get quantum information safely across a lab bench, Pan was already starting to think about how to teleport it across the planet.

First proposed in 1993 by computer scientist Charles Bennett of IBM in New York and his colleagues[4], quantum teleportation earned its sensational name because, "like something out of *Star Trek*", says Chen, it allows all



information about a quantum object to be scanned in one location and then recreated in a new place. The key is entanglement (see 'Quantum at a distance'): because operations carried out on one of the entangled particles affect the state of its partner, no matter how far away it is, the two objects can be manipulated to act like two ends of a quantum telephone line, transmitting quantum information between two widely separated locations.

The challenge arises when entangled particles, which must be produced together, are transmitted to their respective ends of the phone connection. Such a journey is fraught with noise, scattering interactions and all manner of other disruptions, any of which can destroy the delicate quantum correlations required to make teleportation work. Currently, for example, entangled photons are transported through optical fibres. But fibres absorb light, which keeps the photons from travelling more than a few hundred kilometres. Standard amplifiers can't help, because the amplification process will destroy the quantum information. "For teleporting to distances beyond the range of a city, we need to teleport through a satellite," says Chen.

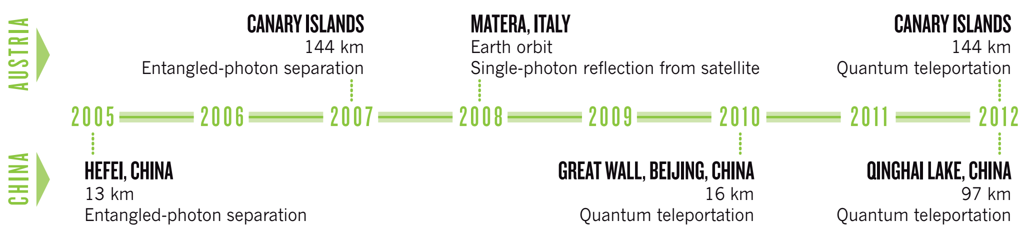
But would entanglement survive the upward trip through Earth's turbulent atmosphere to a satellite hundreds of kilometres overhead? To find out, Pan's team, including Chen, began in 2005 to carry out ground-based feasibility tests across ever-increasing expanses of clear air to find out whether photons lose their entanglement when they bump into air molecules. But they also needed to build a target detector that was both small enough to fit on a satellite and sensitive enough to pick out the teleported photons from background light. And then they had to show that they could focus their photon beam tightly enough to hit the detector.

The work aroused Zeilinger's competitive instincts. "The Chinese were doing it, so we thought, why not try it?" he says with a laugh. "Some friendly competition is always good." The race began to push the distance record farther and farther (see 'Duelling records'). Over the next seven years, through a series of experiments carried out in Hefei, then by the Great Wall in Beijing and finally in Qinghai, the Chinese team teleported over ever-greater distances, until it passed 97 kilometres[5]. The researchers announced their results in May, posting a paper on the physics preprint server, arXiv — much to the chagrin of the Austrian team, which was writing up the results of its own effort to teleport photons between two of the Canary Islands. The Austrian group posted its paper on arXiv eight days later, reporting a new distance record of 143 kilometres[6]. The papers were eventually published, in quick succession, in *Nature*[5,6]. "I think that was in recognition of the fact that each experiment has different and complementary merits," says Xiao-song Ma, a physicist at the University of Vienna and a member of the Austrian team.

Both teams agree that any scientific concerns about teleporting to a satellite have been defused. Now they just need a satellite to host the tests and a functioning payload to put on board. Zeilinger's team had been discussing a possible quantum satellite mission with the European Space Agency

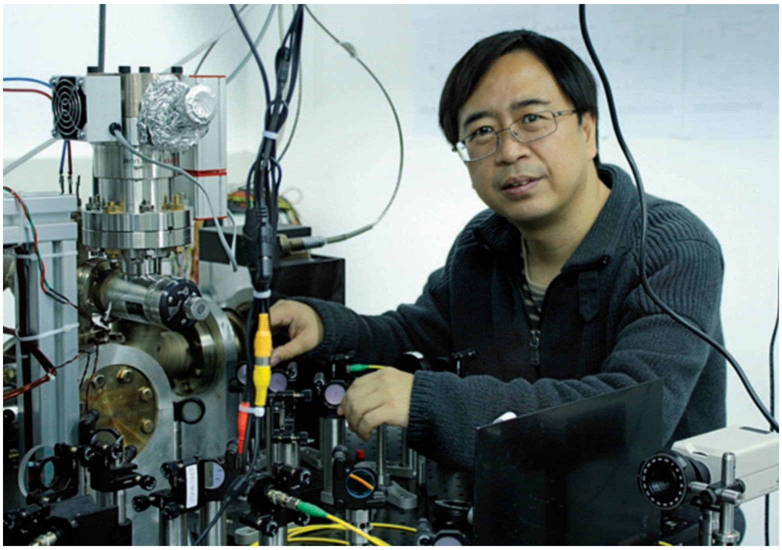
DUELLING RECORDS

Teams based in China and Austria have competed for seven years to establish milestones — first for the separation of entangled particles, which define the ends of a quantum telephone line, and then for the teleportation of information along the line.



"I WAS OBSESSED WITH THESE QUANTUM PARADOXES."

STEFANIE SCHRAMM



Jian-Wei Pan is working on ways to teleport photons between Earth and space.

(ESA), but those talks gradually fizzled out. "Its mechanisms are so slow that no decision was made," says Zeilinger. ESA's hesitation opened up a gap for the China National Space Administration to swoop in. Pan has been instrumental in pushing through the mission, which should see a quantum-physics satellite launched in 2016. This places Pan ahead in the quantum space race, and his team will handle the bulk of the scientific tests.

KEY TO SUCCESS

But there is no point in developing the first global quantum communication network if you do not have anybody to talk with. So Pan has invited his one-time rival to join him on the project. Their first joint goal will be to generate and share a secure quantum key between Beijing and Vienna. "Ultimately, teleporting to a satellite is too big a task for any single group to do alone," says Ma.

Although the promise to push forward the technological frontier has been the main attraction for the Chinese government, many physicists find the satellite project tantalizing for other reasons. "As a scientist, what drives me is learning more about the foundational side of physics," says Chen. So far, quantum theory's weirdness has been replicated time and again in labs, but it has never before been tested across distances that stretch into space — and there is reason to think that if it is going to break down anywhere, it will be there. At these larger scales, another fundamental theory of physics holds sway: general relativity. Relativity portrays time as another dimension interwoven with the three dimensions of space, thereby creating a four-dimensional space-time fabric that comprises the Universe. Gravity manifests because this malleable fabric bends around massive objects such as the Sun and it pulls less-massive objects, such as planets, towards them.

The challenge is that quantum theory and general relativity present fundamentally different conceptions of space and time, and physicists have struggled to meld them into one unifying framework of quantum gravity. In Einstein's picture, space-time is perfectly smooth, even when examined at infinitesimal scales. Quantum uncertainty, however, implies that it is impossible to examine space at such small distances. Somewhere along the line either quantum theory or general relativity, if not both, must give way, but it is not yet clear which. The satellite experiments could help by testing whether the rules of quantum theory still apply over scales across which gravity's pull cannot be ignored.

An obvious question is whether entanglement can stretch between Earth and a satellite. The team plans to answer it by producing a series of entangled particles on the satellite, firing one of each pair down to a ground station and then measuring its properties to verify that the pairs are correlated — and that the equipment is working properly. "If entanglement doesn't survive we'd have to look for an alternative theory to quantum mechanics," says Nicolas Brunner, a theoretical physicist at the University of Geneva, Switzerland, who works on protocols for teleportation to a satellite.

The satellite could also go a step further and probe some of the predictions about the structure of space-time made by candidate quantum-gravity theories. For instance, all such theories predict that space-time would become grainy if scientists could somehow see it at scales of 10^{-35} metres, a characteristic distance known as the Planck length. If that is indeed the case, then photons travelling from the satellite along this grainy road would be very slightly slowed[7] and their polarizations would undergo a tiny, random rotation[8] — effects that could be large enough to be picked up at the ground station. "A satellite will open a truly novel window into a regime that experimenters haven't had access to before — and that is fantastic," says Giovanni Amelino-Camelia, a physicist at the Sapienza University of Rome, Italy.

Pan, Zeilinger and their teams are currently scrutinizing the ideas generated in a recent series of workshops at the Perimeter Institute for Theoretical Physics in Waterloo, Canada, where physicists were asked to come up with other foundational questions that could be tested by satellites[9]. The questions that arose included: how does an entangled particle always know the result of a measurement made on its far-distant partner? Do the pairs somehow communicate though some still-unknown information channel? What causes the quantum wavefunction to collapse when it is measured? Is gravity somehow involved? And is time a precisely defined quantity, as described in general relativity — or is it fuzzy, as might be expected from quantum mechanics?

Answering such questions will require apparatus of extraordinary sensitivity, says Pan. But meeting the technical challenges they raise will be easier now that the teams have joined forces, he says. The Austrian group, too, is seizing the new collaboration with enthusiasm. As Zeilinger says, "One of my students has just started learning Chinese." ■

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