Micius Witnesses "Spooky Action" over 1200km from Outer Space

By SONG Jianlan (Staff Reporter)

CAS scientists reported on June 16 in Science magazine the first successful results from experiments aboard "Micius", the quantum science satellite sent into orbit in August 2016. Apart from laying technical foundation for the country's ambitious plan to set up a wide-area network for quantum communications, these results might help answer some of the open questions in quantum mechanics, which have long puzzled physicists.

A join team of CAS scientists report on June 16 in a cover article in *Science* the first results from the experiments aboard Micius, marking the first successful survival of quantum entanglement over an unprecedented distance of around 2400 km. (Image: *Science*)

"Here we demonstrate satellite-based distribution of entangled photon pairs to two locations separated by 1203 kilometers on Earth, through two satellite-to-ground downlinks with a summed length varying from 1600 to 2400 kilometers," reported a joint research team in a cover article of *Science* on June 16, 2017.

The team has integrated forces from a series of institutions under CAS, including the chief scientist team from the University of Science and Technology of China (USTC, an educational institution under CAS) consisting of Prof. PAN Jianwei, PENG Chengzhi, and their colleagues, together with scientists from other CAS institutes, including Prof. WANG Jianyu and his colleagues from the Shanghai Institute of Technical Physics (SITP), the Institute of Microsatellite Innovation (IMI), the Institute of Optics and Electronics (IOE), the National Astronomical Observatories (NAOC), the Purple Mountain Observatory (PMO), and the National Center of Space Science (NCSS), under sponsorship of the Strategic Priority Research Program on Space Science of the CAS,

This formally announced the first successful entanglement distribution over a distance of thousand-kilometer scale in the world – the longest ever achieved by human beings.

"We observed a survival of two-photon entanglement and a violation of Bell inequality by 2.37 ± 0.09 under strict Einstein locality conditions," the authors further confirmed. Once again, survival distance of the "spooky action", a mysterious quantum phenomenon even baffled Einstein, was extended to an unprecedented distance, with aid from Micius, a satellite developed by CAS.

"Spooky Action" in Outer Space

Dubbed "Micius" after Mozi (Mo-tse), a philosopher of ancient China who explored the pin-hole imaging phenomenon as early as around 2500 years ago, the satellite was sent into space in August 2016 from Jiuquan launching site in northwestern China, to perform three major scientific experiments at space scale, including the satellite-ground quantum entanglement distribution, the distribution of encrypted quantum keys, and the quantum teleportation, aimed at establishing the satellite-ground channel for quantum communications.

Since its launch, Micius has never dropped out of the foci of global attention, given the potentially epochal significance of its mission. Particularly well-awaited has been the result from the entanglement distribution experiment in outer space, in which entangled photon pairs would be separated and each sent to different receivers installed at ground stations located over 1000 km apart. Whether the entanglement could survive the unprecedented distance has hence intrigued scientists and laymen people, as the survival distance ever achieved before by human beings had been limited to merely about 100 kilometers.

Quantum entanglement is a magical action in which quantum particles – photons for example – stay in the same state even if separated far apart. A possible implication of its existence is that one particle of an entangled twin can affect the action of the other afar immediately – at a speed faster than light, apparently violating Albert Einstein's famous assumption underlying his theory of relativity that nothing can travel faster than light. Confused by this instantaneous action, the great physicist described this mysterious phenomenon as "a spooky action at a distance" in 1948.

Paradoxically, the abstruse confusion makes it even more interesting to test whether this "spooky action" can maintain over a very long distance. This magical glamour has prompted physicists to test the "limit distance" of entanglement, contending to extend the survival distance. In 2012, the survival distance was extended to a new scale of hundred kilometers by PAN's team themselves in an experiment performed on the Qinghai-Tibet Plateau.

Rapidly extended as it was, the survival distance seemed to be approaching a threshold, nevertheless. Actually, it is impossible to test its survival on the ground over a very long distance, due to the vulnerability of quantum entanglement itself. No matter what causes its occurrence, it could attenuate sharply while the entangled pairs travel through optic fibers or in near-surface air, as a result from the energy decay caused by the bumps and bounds of photons with the molecules getting in their way.

Theoretically, the survival distance of quantum entanglement can be extended using quantum repeaters, and in this area considerable progress has been made by research groups all over the world, including PAN's team. However, according to PAN, bottlenecked by long storage time and high retrieval efficiency of quantum photons, and particularly the great challenges of simultaneously realizing and integrating all the key capabilities, practical usefulness of repeaters in long-distance entanglement distribution remains a beautiful dream. Scientists hence turn to space for longer accessible distance – the extremely thin air in outer space can largely reduce the energy decay, and therefore considerably increase the potentially available survival distance. Ideally, with help from satellites in combination with ground stations, quantum entanglement distribution at global scale could be achieved.

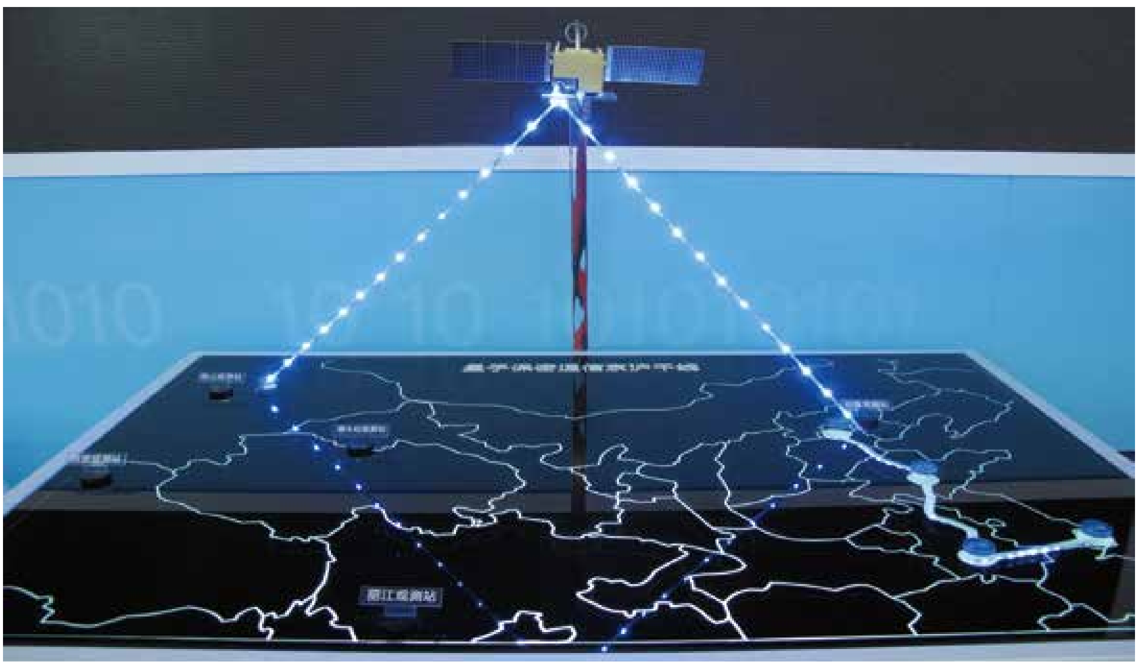
Handshake between Micius and Ground Stations

To perform the satellite-ground quantum experiments, the satellite Micius, at an altitude of 500 kilometers above the earth, needs to join hands with five ground stations which are to receive or emitted the photons: the ground station in Xinglong County in Hebei Province, the one in Ali Prefecture in Tibet Autonomous Region, the Nanshan Observatory in Xinjiang Autonomous Region, the one in Lijiang of Yunnan Province, and the one in Delingha, Qinghai Province, China.

While orbiting over the territorial areas where the Delingha and Lijiang stations are located, the satellite simultaneously established optic down-links to the two stations, respectively, emitting entangled photons to each of them. The overall length of the two downlinks from the satellite to the two stations varied from 1600 to 2400 kilometers, at a tracking accuracy of 0.4 μrad. The source of entangled photon pairs aboard the satellite produced 5.9 million pairs of entangled photons per second, establishing downlinks at a speed of over one pair per second between the satellite and the two involved ground stations. As observed in the experiment, the highest attenuation of quantum entanglement during the transmission was as low as ~82dB at the summed distance of 2400 kilometers, and remained relatively stable, ranging from 64 to 68.5 dB, measuring only one trillionth of the channel loss if transmitted in optic fibers.

"It is like throwing two coins, which are somehow spinning in a synchronized way, simultaneously and separately into two thin slots located 1203 km apart," PAN was quoted describing the astounding accuracy demanded in the experiment after the launching of Micius. What intrigued scientists and the public, however, has not been the technical difficulty of the experiment, but the great suspense whether the entanglement could survive the unprecedented distance and, whether it could be affected by variations in gravity or other forces.

Now comes the answer, after about 10 months'



Illustrated here is a model demonstrating the coordination between the satellite Micius and the five ground stations located in China. The stations in Nanshan, Delingha and Lijiang were the ones that received the entangled photons in the published experiment for entanglement distribution. (Photo by Song JL)

Shown here is a time-lapse exposure (10 to15 seconds) image taken by the team during the satellite's passing over the Nanshan optical ground station (OGS). The green line is the bacon laser from the satellite to the ground, and the red light the bacon laser from the ground station to the satellite. (Photo by ZHU Jin)

waiting. In their paper, the team confirmed that they observed a survival of two-photon entanglement and a violation of Bell inequality by 2.37 ± 0.09 under strict Einstein locality conditions, based on their analysis of data from the satellite-ground bi-directional experiment.

Testing Bell Inequality

Together with his colleagues Boris Podolsky and Nathan Rosen, Einstein challenged quantum mechanics in a thought experiment named the Einstein-Podolsky-Rosen paradox, short as the "EPR paradox". Based on this paradox, David Bohm *et al.* proposed the "hidden variable theory", to explain quantum entanglement within the framework of relativity theory, posing a further challenge to the completeness of quantum mechanics. On the other hand, John Stewart Bell proposed a theorem described as "Bell's inequality" to determine whether quantum mechanics or the "hidden variable theory", which supports the "EPR paradox", is right. If experimental observations support Bell's inequality, Einstein will be proven to be right; on the contrary, if the experiments violate Bell's inequality, Einstein's belief will be weakened.

A series of experiments have been performed over the past years to test this theorem, remarkable among which was the loophole-free Bell inequality measurement made by Dutch physicists in 2015. Aboard Micius are also a series of experiments aimed to verifying if Bell inequality holds. Naturally, these experiments have remained a focus of attention.

PAN's team ran 1167 trials of the Bell test during an effective time of 1059 s. The data observed indicated a violation of the CHSH-type Bell inequality $S \leq 2$ by four standard deviations, once again confirming the nonlocal feature of entanglement and excludes the models of reality that rest on the notions of locality and realism, on a previously unattained scale of thousands of kilometers.

While fueling the debate on some very fundamental scientific questions in quantum mechanics, the results are deemed to have offered technical possibility for further satellite-based experimental verification of fundamental principles in general quantum mechanics and quantum gravity in outer space, hence might have far-reaching influence on research in this field.

On the other hand, it is also thought to have laid a reliable technical foundation for further experimental research on scalable quantum networks and quantum communications, contributing to the development of scalable networks for encrypted quantum communications.

More to Come from Space

Actually, as early as in 2003, PAN's team already proposed the ambitious strategy to distribute entangled photon pairs from outer space via a satellite. Their ensuing endeavors and successes in the following decade gradually helped them make the dream true.

Before long, the year 2005 witnessed their triumph in bi-directional distribution of entangled quantum pairs over a distance of 13 kilometers (larger than the vertical thickness of the atmosphere) in free space. In the year 2010, they broke the world record set by themselves by achieving teleportation over 16 kilometers based on distribution of entangled quantum pairs. The next year, the team's proposal on Micius won the support from the CAS Strategic Priority Research Program and a special project was hence formally set up under its sponsorship, namely the Strategic Priority Research Program on Space Science. Further in the year of 2012, they succeed in extending the safety distance of free-space quantum communication to a hundred-kilometer scale by achieving bi-directional quantum entanglement distribution and quantum teleportation over the Qinghai Lake on the Qinghai-Tibet Plateau, solidly demonstrating the feasibility of quantum communications via satellites.

The long-term buildup and persistent hard work eventually helped the team succeed in developing and building the payload of Micius, and further obtained the first successful results.

The published results just represented the first part what Micius will present, however. Other important scientific experiments aboard the satellite, including the high-speed satellite-to-ground quantum key distribution and the ground-to-satellite quantum teleportation, are anticipated to yield more results later this year.

More notably, the good news about the experiment of quantum entanglement distribution came only one day after the launching of the "Intellectual Eye", namely the space-based Hard X-ray Modulation Telescope (HXMT), another micro-satellite developed by CAS aimed at science research supported by the Strategic Priority Research Program on Space Science sponsored by CAS. Both satellites are part of the Academy's plan to boost science research by virtue of space technologies. For this sake, a total of four satellites aimed at scientific research have been launched since late 2015, and five more are coming in the next five years.

For more information please refer to:

Yin *et al*., Satellite-based entanglement distribution over 1200 kilometers, *Science* 356, 1140–1144 (2017).