Physicists test real quantum theory in an optical quantum network

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Zheng-Da Li and Ya-Li Mao preparing the experiment. Credit: Li et al.

Quantum theory was originally formulated using complex numbers. Nonetheless, when replying to a letter by Hendrik Lorenz, Erwin Schrödinger (one of its founding fathers), wrote: "Using complex numbers in quantum theory is unpleasant and should be objected to. The wave function is surely fundamentally a real function."

In recent years, scientists successfully ruled out any local hidden variable explanation of quantum theory using Bell tests. Later, such tests were generalized to a network with multiple independent hidden variables. In such a quantum network, quantum theory with only real numbers, or "real quantum theory," and standard quantum theory make quantitatively different predictions in some scenarios, enabling experimental tests of the validity of real quantum theory.

Researchers at Southern University of Science and Technology in China, the Austrian Academy of Sciences and other institutes worldwide have recently adapted one of these tests so that they could be implemented in state-of-the-art photonic systems. Their paper, published in *Physical Review Letters*, experimentally demonstrates the existence of quantum correlations in an optical network that cannot be explained by real quantum theory.

"From the early days of quantum theory, complex numbers were treated more as a mathematical connivence than a fundamental building block," Zizhu Wang, one of the researchers who carried out the study, told Phys.org. "The general debate on the role of complex numbers in quantum theory has continued into the present."

In the 1960s, the Swiss physicist Ernst Stueckelberg and his colleagues successfully formulated quantum theory in real Hilbert spaces. While this was an important milestone in the field, their formulation did not use the renowned, so-called "tensor product" to compose different systems. This essentially means that their formulation is not consistent with what is known as "real quantum theory."

"Interest in this question was revived when we started looking at quantum theory from an information-theoretic perspective," Wang explained. "Some generalized probabilistic theories (GPTs), formulated using only real numbers, turn out to be as powerful as quantum theory in some information processing tasks, and even outperform quantum theory in some others. Even though we know GPTs contain correlations beyond quantum theory, we did not have the tools to definitively rule out real quantum theory as a viable alternative to complex quantum theory, until now."

The recent paper by Fan and his colleagues draws inspiration from a long-standing debate in the physics field, namely that pertaining to the existence of local hidden variables in quantum theory. Physicists Albert Einstein, Boris Podolsky and Nathan Rosen posed this important question in one of their seminal papers, published in 1935. While many physicists explored this question in later years, for decades no one was able to devise a concrete method to test whether these local hidden variables exist.

"In 1964, John Bell came up with the revolutionary idea of using correlations functions of probabilities, which can be tested and analyzed in a laboratory, to infer underlying properties of physical systems," Jingyun Fan, another researcher involved in the study, told Phys.org. "It took another 50 years to finally settle this debate and systematically rule out local hidden variable explanations of quantum theory."

While it has been successfully applied in many studies, Bell's theorem alone is not powerful enough to accurately predict the differences between real and complex quantum theories. In their recent study, Fan and his colleagues were able to assess these differences by considering a quantum network with multiple, independent sources.

"Recently, a team of theorists, including Miguel Navascués, Mirjam Weilenmann, Armin Tavakoli, David Trillo and Thinh P. Le from Vienna, Antonio Acín, Marc-Olivier Renou from Barcelona and Nicolas Gisin from Geneva, realized that a natural generalization of Bell test in a network can distinguish complex quantum theory from real quantum theory," Fan said. "In a network in which parties are connected through several independent entanglement sources real quantum theory does not agree with all predictions of complex quantum theory. This paves the way for experimentally distinguishing between the two theories in a quantum network based on independent entanglement sources."

To implement and test the theory devised by Navascués and his colleagues in an experimental setting, the researchers used a state-of-the-art optical quantum network. A key assumption of the theory is source independence, which implies that the analyzed network should consist of independent entanglement sources, producing pairs of entangled states.

The theory suggests that when this assumption is not met, predictions become invalid. To ensure that it was met in their experiments, Fan and his colleagues thus used a photonic network in which sources of entangled photons are physically separated.

"Another experimental challenge is that the experimental system must be clean with very little noise," Fan said. "A team of scientists, including Zhengda Li, Yali Mao, Hu Chen, Lixin Feng, Shengjun Yang and myself from Southern University of Science and Technology in Shenzhen and Zizhu Wang from the University of Electronic Science and Technology of China in Chengdu, the city famous for its pandas, overcame these challenges," Fan said. "We constructed a quantum network experiment with two independent entanglement sources and three parties (i.e., Alice, Bob and Charlie) and observed correlations violating the constraints of real quantum theory by over 4.5 standard deviations."

In contrast with the experimental test carried out by Fan and his colleagues, standard tests based on Bell's theory only employ a single entanglement source and considers two parties (i.e., Alice and Bob). Their experimental setting thus allowed the researchers to overcome the challenges associated with standard Bell's theorem-based tests and to effectively test the differences between real and complex quantum theories.

"Our experiment necessarily disproves real quantum theory as a universal physical theory, clearly showing that not all predictions based on standard quantum theory with complex numbers can be modeled by the real-number analog of standard quantum theory," Fan said. "Hence, complex numbers are fundamental to quantum theory."

In the future, the recent study carried out by this team of researchers could pave the way for further research assessing the foundations of quantum physics, particularly in quantum networks. Ultimately, this could enable the development of new innovative quantum technologies and applications, as Bell's theorem is widely used in quantum information science.

"While the Bell nonlocality of a bipartite system is already counter-intuitive, multipartite nonlocality in our many-body world turns out to be even more so: nature's correlations are boundlessly multipartite nonlocal," Fan added. "Interestingly, we just developed a Bell-type test for genuine multipartite nonlocality in network to show that nature is boundless multipartite nonlocal and conducted the first experiment."

More information: Zheng-Da Li et al, Testing Real Quantum Theory in an Optical Quantum Network, *Physical Review Letters* (2022). DOI: 10.1103/PhysRevLett.128.040402

Ya-Li Mao, Zheng-Da Li, Sixia Yu, Jingyun Fan, Test of genuine multipartite nonlocality. arXiv:2201.12753v2 [quant-ph], arxiv.org/abs/2201.12753