The Road to and from Quantum Entanglement Experiments

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Four articles by Nicolas Gisin, Jian-Wei Pan, Emanuele Polino & Fabio Sciarrino and Marek Zukowski provide an overview of the history of quantum foundations, from the early pioneer to today's quantum information research - the significance of which was recognized by the 2022 Nobel Prize awarded to Alain Aspect, John F. Clauser and Anton Zeilinger. They also write about the future development of quantum information science and shared their thoughts on how this new technology could in turn enable addressing new questions in fundamental physics.

In their independent historical tour de forces, Gisin and Zukowski recall that the initial discussion on the foundations of quantum mechanics triggered by the Bohr-Einstein dialogue was soon replaced by the culture of "shut-up-and-calculate", in which working on quantum foundations was "a kind of scientific suicide". What has changed the physics community's perception of the research field so dramatically since then? The two authors give three reasons for this change. First, some researchers, most notably John Bell, and the three Nobel laureates, did not follow the crowd and continued to work on fundamental questions. Secondly, advances in quantum optics made the "thought experiments" of the Bohr-Einstein debate feasible. And finally, these developments eventually led to quantum information science and technology. For example, the spontaneous parametric down-conversion source became the workhorse in experimental tests of Bell's inequalities, and was instrumental in demonstrating new ideas such as quantum teleportation, superdense coding or entanglement swapping. In parallel, the development of single photon detectors not only enabled the demonstration of quantum key distribution, but also to industrialize and commercialize it.

In their articles, Pan and independently Polino & Sciarrino focus on the use of emerging quantum technology for new frontiers in physics and the implementation in quantum networks and quantum metrology. Pan presents the vision of a global quantum network that began with the launch of the first quantum satellite, Micius, in China in August 2016. A series of experiments established the satellite-based free-space quantum link, connecting multiple ground stations. In future, a space-based platform could enable fundamental experiments over distances that were previously inaccessible on the ground. For example, the interface between gravity and quantum physics or the applicability of quantum theory at larger length scales can be tested. Polino and Sciarrino write about realizations of photonic quantum networks violating classical causal constraints beyond the simple Bell scenario. They also identify open challenges to be faced in the research area: the characterization of the classical-quantum gap in complex networks and exploration of different causal structures with independent entanglement sources and entangling measurements. ■

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