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Celebrating entanglement

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The 2022 Nobel Prize in Physics celebrates the profound impact of quantum entanglement, which underpins many modern quantum technologies such as quantum cryptography and computing.

Given the core role it plays in making quantum technologies truly quantum in their nature and capabilities it seems that the validation of quantum entanglement (or "spooky action at a distance" as Einstein called it) is a well-deserved topic for a Nobel Prize. On October 2022, the Royal Swedish Academy of Sciences announced that this year's Nobel Prize in Physics was being jointly awarded to Alain Aspect, John F. Clauser and Anton Zeilinger "for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science".

Today, the concept of entangled photons is recognized as one of the key underlying foundations of quantum technologies, with research in the area often covered in *Nature Photonics*. However, it's not always been that way. In the 1930s, the early days of quantum mechanics, the nature of the mutual interaction between a pair of quantum particles with a common birth was controversial, with two competing theories being actively discussed. One idea was that the interaction between the pair could be accounted for by an undiscovered mechanism as represented by hidden variables[1]. The alternative theory implied the intrinsic non-locality characteristics of quantum mechanics, that is, entanglement[2].

Entanglement implies that even if a pair of particles A and B generated from a particle with spin state 0 is infinitely separated in space, the spin state of particle B is instantaneously determined by the measurement of the spin state of particle A. The pressing problem is how one can experimentally verify or rule out the existence of an undiscovered mechanism operating through hidden variables that can transmit the information about the spin state from the particle A to B instantaneously, that is, faster than the speed of light. It was physicist John Stewart Bell who in 1964 offered a way forward to settle the debate between the existence of hidden variables or the validity of entanglement with his formulation of the now famous Bell inequality[3]. If experimental results fulfil this inequality, then the hidden variable theory is correct. If not, then entanglement is responsible. Testing this inequality was thus expected to settle the dispute about the identity of the mutual interactions. However, it was not a straightforward task, because the thought experiment proposed by Bell required photon source and detector technology that was not yet available.

John Clauser had an intense interest in Bell's paper, and contemplated how the technical issues associated with a test of the Bell inequality could be mitigated experimentally. In 1969, John Clauser, Michael Horne, Abner Shimony and Richard Holt jointly proposed a test called the CHSH inequality, after their surnames[4].

For the verification experiment, Clauser and doctoral student Stuart Freedman employed polarization states of pairs of photons generated from optically excited calcium atoms. After two years spent building an experimental apparatus able to measure arbitrary polarization states of photon pairs at two locations separated by about 3 m, Clauser and Freedman experimentally showed a clear violation of the CHSH inequality[5], suggesting that the mutual interaction cannot be explained by hidden variables.

However, there was a loophole in the measurement by Clauser and Freedman. Since the direction of polarizers was pre-set before the emission of the photon pairs, the measurement outcomes of the polarization states could in principle still be affected via an undiscovered mechanism, thus reigniting the debate.

Alain Aspect also felt that the measurement with pre-set polarizer was problematic. He thought that this loophole could be closed if the direction of two polarizers was arbitrarily changed during photon propagation. When Aspect told Bell about his idea, Bell strongly recommend to publish it as soon as possible[6]. In order to close the loophole, Aspect's group demonstrated the efficient generation of photon pairs[7], and adopted two-channel polarizers[8] and acousto-optical switches[9]. Thanks to the loophole-closed experimental apparatus, Aspect's group unambiguously showed the violation of the CHSH inequality: quantum mechanics is correct and hidden variables don't exist.

Entanglement is thus a real effect that lies at the heart of quantum mechanics and is central to both fundamental research and applied technology. A good example of the power of entanglement is quantum teleportation developed by Anton Zeilinger and his co-workers in 1997[10]. According to quantum mechanics, it is impossible to create an identical copy of a quantum state without destroying the original, that is, the no cloning theorem. However, with the help of quantum teleportation, quantum states of photons can be transferred between photons. This unique feature is expected to be applied to a variety of quantum technologies such as tap-proof cryptographic communications and quantum computers significantly surpassing the performance of supercomputers[11]. The research on entangled photons by the three Nobel Prize awardees undoubtedly confirmed and opened a new important research avenue in physics.

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