Editorial

https://doi.org/10.1038/s41567-022-01847-x

Time for a different Nobel prediction

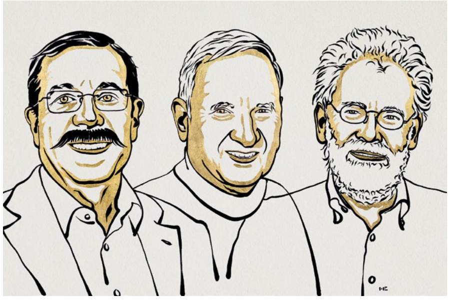
The 2022 Nobel Prize in Physics has been awarded "for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science", a long-anticipated topic for the prize.

For a long time fans of quantum physics have had an easy answer when asked to guess potential Nobel Prize winners: Alain Aspect, John Clauser and Anton Zeilinger, for their experiments exploring the physics of entanglement. We made such a prediction ourselves in 2010[1] after the same work was recognized by the Wolf Prize, often regarded as an identifier of future Nobel candidates. They are the winners of this year's Nobel Prize in Physics.

When two particles are entangled, measurements of each particle's state are correlated in a way that cannot be explained by classical physics. The effect persists even if the particles are so far apart that no signal could connect the two measurement events without violating the laws of relativity. This behaviour presents serious challenges to classical intuition and so it is not surprising that much of the coverage of this year's prize has focused on explaining its conceptual background.

From recollections of the prizewinners and their contemporaries[2] it is clear that following the establishment and success of quantum mechanics, there was a serious reluctance among the physics community to explore the conceptual challenges the theory posed. It took decades before researchers such as the theorist John Bell engaged seriously with the possibility of alternative theories that explain the correlations between entangled particles by assigning them inaccessible 'hidden variables'. As part of this work, Bell developed an inequality that would be satisfied by a large class of hidden variable theories but is violated by quantum theory, rendering them experimentally distinguishable.

This year's prizewinners developed and performed practical experiments based on Bell's inequality, ruling out many of the most attractive hidden-variable theories. All three specialized in quantum optics, using pairs of entangled photons as the basis for their 'Bell tests'. Over time, the experiments have been performed with increasing sophistication in order to exclude as many alternative theories as possible. For example, the scale and timing of the first experiment by Clauser and Stuart Freedman[3] would have allowed for the measurements to influence each other without violating special relativity. By ingenious experimental design, many 'loopholes' of this kind have now been closed.



Quantum physicists are now well accustomed to experiments confirming our existing theories of the foundations of physics. As many physicists outside the field will tell you, one can get quite a lot done using quantum physics without being affected by the details of entanglement celebrated by this year's Nobel Prize.

However, the confirmation of quantum mechanical predictions should not be taken for granted. The first Bell tests were performed in the 1970s and 1980s when much of our current understanding of fundamental physics was still being established and confirmed. In a world where Bell inequality violation had never been observed the consensus view of quantum mechanics would be quite different.

Quantum optics experiments of the kind used by this year's laureates remain a key platform to rigorously test quantum mechanics. The understanding of the structure and meaning of quantum mechanics continues to develop. New theoretical ideas are often quickly followed up by verifications using quantum optical methods. For example, an experiment to confirm that the mathematical structure of complex numbers is required in quantum mechanics[4] was performed in a matter of months after it was first proposed[5,6].

Beyond the foundations of physics, the understanding of entanglement that has emerged following the laureates' experiments is at the heart of modern quantum information science. Entanglement is now viewed as a resource that plays a key role in the success of quantum computing and other quantum technologies.

The correlations responsible for Bell inequality violations can be exploited to confirm a quantum device is working without accidental or malicious interference. This enables device-independent cryptographic protocols with security guarantees that don't require trust or careful certification of equipment. Quantum teleportation – the transfer of a quantum state from one location to another by exploiting entanglement – was first realized in Zeilinger's group in 1997[7] and is now the technological basis for proposed quantum communication networks.

Many of these applications, at least at the conceptual level, require only pairs of entangled photons. However, designs for scalable quantum computers involve entanglement between many different particles at once. Several quantum optics groups are working to realize measurement-based quantum computing[8]. In this approach calculations are performed by measuring a special, large, highly entangled quantum state. Efforts such as these to create and manipulate ever more complicated quantum states continue to test physicists' experimental and theoretical mastery over entanglement.

Experimental quantum physics has advanced rapidly over the last couple of decades, with a pace that appears to be accelerating. Quantum physics enthusiasts will probably anticipate a Nobel Prize building on the work of this years' winners in the near future.

References

1. *Nat. Phys.* **6**, 395 (2010).
2. Bertlmann, R. A. & Zeilinger, A. *Quantum (Un)speakables* (Springer, 2002).
3. Freedman, S. J. & Clauser, J. F. *Phys. Rev. Lett.* **28**, 938–941 (1972).
4. Renou, M. O. et al. *Nature* **600**, 625–629 (2021).
5. Li, Z.-D. et al. *Phys. Rev. Lett.* **128**, 040402 (2022).
6. Chen, M.-C. et al. *Phys. Rev. Lett.* **128**, 040403 (2022).
7. Bouwmeester, D. et al. *Nature* **390**, 575–579 (1997).
8. Briegel, H. J., Browne, D. E., Dür, W., Raussendorf, R. & Van den Nest, M. *Nat. Phys.* **5**, 19–26 (2009).

CREDITS: © NOBEL PRIZE OUTREACH. ILLUSTRATION: NIKLAS ELMEHED.