# The 2022 Nobel Prize in Physics

The 2022 Nobel Prize in Physics has been awarded to John F. Clauser, Alain Aspect and Anton Zeilinger 'for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science'[1]. The trio was also awarded the Wolf Prize in Physics in 2010. Clauser built on Bell's ideas, leading to a practical experiment. Aspect further developed the set-up, closing the communication loophole. Zeilinger used entangled states, with refined tools in a series of experiments, demonstrating quantum teleportation among other aspects. The technological progress achieved in these works confirmed the quantum theory predictions.

Clauser is an American physicist who received his B.S. in physics from Caltech in 1964. He then obtained his M.A. in physics in 1966 and his Ph.D. in physics in 1969 from Columbia University. Thereafter, he joined the University of California, Berkeley, as a postdoctoral researcher and continued as a research physicist at the Lawrence Livermore National Laboratory and the Lawrence Berkeley National Laboratory till 1996. Since then he has been running his own company, J. F. Clauser and Associates, as a consultant and an inventor, working on interferometry and quantum theory.

Aspect is a French physicist who received his Bachelor's degree in physics from ENS Cachan in 1969. He then obtained his Master's and Ph.D. degrees from the Université d'Orsay in 1971 and 1983 respectively. Subsequently, he has worked in atomic physics and quantum optics, holding positions at the Collège de France, the Laboratoire Charles Fabry de l'Institut d'Optique and the École Polytechnique. At present, he is a distinguished scientist emeritus at the CNRS.

Zeilinger is an Austrian physicist who attended the University of Vienna, studying physics there from 1963 to 1971 and graduating with a doctorate. He then served as a research assistant at the Atominstitut Vienna, and as a research associate at MIT, USA, before becoming an assistant professor at Atominstitut Vienna in 1979. In the 1980s and 1990s, he held professorships at the Vienna University of Technology, the Technical University of Munich, the University of Innsbruck and the University of Vienna. He also served as the Scientific Director at the Institute for Quantum Optics and Quantum Information Vienna between 2004 and 2013, and as the President of the Austrian Academy of Sciences from 2013 to 2022.

## Background

The question of interpretation of quantum mechanics goes all the way back to its origin. Even though Einstein contributed to many early developments in quantum mechanics, he was uncomfortable with its probability interpretation. He was not satisfied with quantum mechanics being treated as an empirical theory; he wanted it to arise from a deterministic underlying structure, similar to how macroscopic statistical mechanics arises from microscopic atomic-scale phenomena. The EPR paper posed this question directly[2]: Can quantum-mechanical description of physical reality be considered complete?

Bohr responded to the EPR paper, in the same journal, with the same title. He reiterated his Copenhagen interpretation, and that did not attract much attention. Schrödinger responded as well, sharpening Einstein's question. That response is remembered well for the two concepts he introduced. One is that of 'entanglement', i.e. unusual quantum correlations between two separated parts of a system[3]. The other is that of a 'cat' (named after him), which could be dead or alive depending on the occurrence of a quantum event[4]. The philosophical debate on these peculiarities, often referred to as the 'hidden variable' problem, still goes on.

Subsequently, Bohm[5] rephrased the question of quantum correlations in the setting of a finite dimensional system, which turned out to be crucial for performing accurate experimental tests. For this setting, Bell[6] showed that the observable correlations must obey an inequality, when the hidden variables of quantum theory satisfy certain properties. This analysis has been extended to different quantum systems and different observable correlations, and has generated a lot of discussion about interpretation of quantum mechanics[7]. The 2022 Nobel Prize winners performed accurate experiments which demonstrated that the Bell inequality is clearly violated by quantum correlations between two photons produced in a singlet state.

## The fundamental conundrum

At the heart of the interpretation of quantum mechanics is a quandary described by two Greek words, viz. ontology and epistemology. The former concerns determining what is real, irrespective of the observers. The latter focuses on what is observable in practice, and that may depend on the capability of the observer.

It is well-established that quantum dynamics produces probabilistic outcomes, and the measurement postulate of quantum mechanics successfully gives the prescription to predict the probability distribution. However, what has remained mysterious is how and why the probabilistic outcomes arise, and whether the observer plays any role in the same. Probabilistic description of physical phenomena is routine in statistical physics. It is understood as arising from an ensemble of underlying dynamics, which is unobserved and hence summed (or integrated) over all possibilities that may occur. The mystery then is: Can the quantum indeterminacy be explained as arising from so far unobserved 'hidden variables'?

The use of 'effective theories', valid within specific ranges of their degrees of freedom, is widespread in physics. Such theories provide an excellent description of the observed data in terms of certain empirically adjusted parameters. These parameters are understood to be consequences of the unobserved degrees of freedom (apart from fundamental constants), and carry information about their dynamics. For example, a fluid is generally described as a continuous medium, while its properties such as temperature, density and pressure parametrize the underlying atomic dynamics. Moreover, the underlying atomic dynamics produces observable signals in certain correlations, such as the Brownian motion of a particle in a fluid and the fluctuation–dissipation relation.

The hidden variables of quantum mechanics must have a distribution to produce probabilistic outcomes. Even when they are integrated out, they would leave behind observable parameters and contributions to correlations. The question then is whether we can learn something about the properties of the hidden variables by observing their consequences in the effective description. It is in this sense that the peculiarities of quantum correlations takes the centre stage in trying to figure out the nature of the hidden variables.

It should be noted that physical parameters and correlations arising from global conservation laws do not conflict with the locality of relativity. They represent certain symmetries of the overall dynamics, and are part of inherent features of nature. For example, when a firecracker bursts and one half of it is found at one place, it can be immediately inferred that the other half went in the opposite direction (as dictated by the conservation of momentum) without making a separate observation or worrying about instantaneous communication of information. The peculiarities of quantum correlations go beyond such situations and that was emphatically illustrated by Bell.

## Bell inequality

The quantum correlations pointed out by EPR, and rephrased by Bohm, concern two-particle singlet states, created at a common origin and then evolved so that the two components appear at a space-like separation. In the case of photons, such situations arise in the two-photon cascade transitions of certain atoms, or the two-photon decay of a neutral pion, where both the initial and the final states have zero total momentum and zero total angular momentum. The zero momentum implies that the two photons fly off in opposite directions, while the zero angular momentum implies that the internal states of the two photons are anti-correlated in terms of their spins or polarizations. The quantum mechanical description of this entangled singlet internal state is: $|\psi_{12}\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$. If only one of the photons is observed, it is found to be in either $|\uparrow\rangle$ or $|\downarrow\rangle$ state with equal probabilities.

Now consider the situation where two space-like separated observers *A* and *B* measure the two photon spins along non-parallel and non-orthogonal directions, say $\vec{a}$ and $\vec{b}$. The measurement outcomes are then probabilistic, and let us label them as $A(\vec{a}),\ B(\vec{b}) \in \{\pm 1\}$. The directions are chosen such that conservation of angular momentum offers no relation between $A(\vec{a})$ and $B(\vec{b})$, and the property to be investigated is the correlation between the two.

Next, since the two photons have a common origin, let us imagine that the distributions of $A(\vec{a})$ and $B(\vec{b})$ arise from some common ensemble of underlying hidden variables $\{\lambda\}$. The hidden variables appear at the point of origin of the two photons and are then carried by the photons till the points of their observation. We assign to the ensemble of hidden variables a normalized weight distribution $\rho(\lambda)$, with $\int d\lambda\ \rho(\lambda) = 1$, and relabel the measurement outcomes as $A(\vec{a}, \lambda)$ and $B(\vec{b}, \lambda)$ to express their implicit dependence on the hidden variables.

The two-point correlation of the measurement outcomes is: $P(\vec{a}, \vec{b}) = \int d\lambda\ \rho(\lambda)\ A(\vec{a}, \lambda)\ B(\vec{b}, \lambda)$, and the global spin conservation implies $B(\vec{b}, \lambda) = -A(\vec{b}, \lambda)$. Then, using the property that $A(\vec{b}, \lambda)^2 = 1$, we can construct the difference of correlations:

$$P(\vec{a}, \vec{c}) - P(\vec{a}, \vec{b}) = \int d\lambda \rho(\lambda)\ A(\vec{a}, \lambda) \times A(\vec{b}, \lambda)\,[1 - A(\vec{b}, \lambda)\ A(\vec{c}, \lambda)].$$

This difference obeys a simple bound, following from the triangle inequality $|x + y| \le |x| + |y|$ (the sum can be replaced by an integral).

$$|P(\vec{a}, \vec{c}) - P(\vec{a}, \vec{b})| \le \int d\lambda\, \underbrace{|\rho(\lambda)|}_{\ge 0} \times \underbrace{|A(\vec{a}, \lambda) A(\vec{b}, \lambda)|}_{=1} \times \underbrace{|[1 - A(\vec{b}, \lambda)\ A(\vec{c}, \lambda)]|}_{\ge 0} = 1 + P(\vec{b}, \vec{c}).$$

Here the simplification uses the properties indicated below the equation; the last factor of the integrand is non-negative and so the absolute value sign is dropped; the middle factor of the integrand is dropped since it is equal to one, and the absolute value sign of the first factor is dropped assuming that the ensemble weight of the hidden variables is non-negative.

In quantum mechanics, the spin (or polarization) operator producing the measurement outcome $A(\vec{a}, \lambda)$ is $\vec{\sigma}_1 \cdot \vec{a} \equiv (\sigma_1)_x a_x + (\sigma_1)_y a_y + (\sigma_1)_z a_z$. The two-point correlation is then $P(\vec{a}, \vec{b}) = \langle (\vec{\sigma}_1 \cdot \vec{a})(\vec{\sigma}_2 \cdot \vec{b}) \rangle = -\vec{a} \cdot \vec{b}$, due to anti-correlation of the spin components $(\sigma_1)_i$ and $(\sigma_2)_i$. This correlation violates the bound derived above for many choices of $\vec{a}, \vec{b}, \vec{c}$. For example, choosing the directions $\vec{a} = \uparrow, \vec{b} = \nearrow, \vec{c} = \rightarrow$ in two-dimensional space yields: $P(\vec{a}, \vec{b}) = -\frac{1}{\sqrt{2}} = P(\vec{b}, \vec{c})$ and $P(\vec{a}, \vec{c}) = 0$, while $|0 + \frac{1}{\sqrt{2}}| \not\le 1 - \frac{1}{\sqrt{2}}$.

## Bell test experiments

Bell's derivation of the two-photon correlation inequality provided a clear target for experimentalists to test. Of course, they had to develop the technology that would produce reliable singlet photon-pair sources, detect single photons with high success rate and measure their polarizations to high accuracy. They also had to close many loopholes, so that the observed correlations connect to the hidden variable properties and not to other extraneous coincidences. These developments occurred in several stages.

Compared to the preceding correlation check described by Bell, a modified version proposed by Clauser–Horne–Shimony–Holt (CHSH) is easier to implement experimentally[8]. In this version, *A* chooses one of two polarization measurement directions differing by angle $\frac{\pi}{4}$, *B* does the same, and *B*'s measurement directions are rotated from those of *A* by angle $\frac{\pi}{8}$. A linear combination of the four possible polarization correlations (labelled by the measurement directions $\vec{a}, \vec{a}', \vec{b}, \vec{b}'$) then satisfies a Bell-type inequality:

$$|P(\vec{a}, \vec{b}) + P(\vec{a}, \vec{b}') + P(\vec{a}', \vec{b}) - P(\vec{a}', \vec{b}')| \le 2.$$

Having contributed to the CHSH proposal as a graduate student, Clauser took up the challenge to test the inequality as a post-doctoral fellow at Berkeley. He did not have research funds. So the experiment was carried out using borrowed equipment and some discarded parts in a basement laboratory, together with graduate student Freedman. Calcium atoms were used to generate entangled photon pairs and the four correlation terms of the CHSH inequality were measured one by one. The observed correlation results clearly violated the inequality, asserting the peculiar nature of quantum correlations.

The Clauser–Freedman experiment did not test the assumption made by Bell that there is no communication of any information between the measurements performed by *A* and *B*. Aspect and his collaborators at Orsay overcame this shortcoming by refining the experiment. The entangled photon pairs were generated at a higher rate, and the polarization measurement directions on either side were randomly switched at a rate faster than the time light took to travel between *A* and *B*. The observed violation of the CHSH inequality was stronger and in accordance with the quantum mechanical prediction.

Zeilinger and his collaborators at Innsbruck and Vienna later conducted more refined tests of Bell-type inequalities. For CHSH inequality tests, entangled photon pairs were created by shining a laser on a special crystal, and random numbers switching between polarization measurement directions were constructed using signals from distant galaxies to rule out any bias. Quantum teleportation was demonstrated using a two-photon entangled state, where the quantum state of a photon disappeared from one location and reappeared at a distant location without any material transfer. It was extended to entanglement swapping, creating a quantum entangled state between two parties who have not interacted in the past. Furthermore, three-photon quantum correlated states, referred to as the GHZ states, were proposed and physically realized; they provide a deterministic separation (in contrast to probabilistic expectation values) between answers predicted by a Bell-type analysis and physical quantum measurement.

## The way out

The achievement of Clauser, Aspect and Zeilinger is to demonstrate that the experimentally observed two-photon correlations agree with the standard quantum mechanical analysis and disagree with Bell's constraints derived using hidden variables with certain properties. Since then, analogous tests have been carried out for many other correlations and each time the results have confirmed quantum mechanical predictions. This fact reiterates the fundamental question: What is the origin of the peculiar quantum correlations? Obviously, at least one of the assumptions in Bell's derivation must be given up. We do not want to give up the conservation laws or causality, because that would destroy the framework of physics at its core. Also, quantum dynamics and special relativity have been successfully merged in quantum field theory and verified to a fantastic level of accuracy. So we know that there is no need to give up one or the other. We need to therefore inspect the more subtle ingredients in Bell's analysis to find a credible interpretation of quantum mechanics.

### *Give up locality*

This is the frequently used label, i.e. quantum mechanics is non-local. (It does not mean the same thing as existence of non-local quantum correlations, which the experiments verify.) Some of the hidden variables in this case are non-local and unobservable (to avoid conflict with special relativity) and the de Broglie–Bohm theory is an explicit example of this scenario.

### *Give up statistical independence*

This is a difficult-to-overcome loophole. In this case, the hidden variables in some way depend on the measurement settings; so the observables are influenced by the measurement apparatus. Superdeterministic, retrocausal and supermeasured theories with such properties have been constructed, keeping in mind the fact that correlation is not the same as causation.

### *Give up positivity*

This is how the standard formulation of quantum mechanics works, without giving up locality or statistical independence. The quantum ensemble weights are allowed to be negative, i.e. $\rho(\lambda) \ngeq 0$. Indeed, the quantum density matrix is such a weight, with $\mathrm{Tr}(\rho O)$ providing the expectation value of a physical observable $O$. The density matrix is a Hermitian generalization of the classical probability distribution, and its off-diagonal elements contribute to the quantum correlations tested with non-parallel and non-orthogonal directions. In the Wigner function form[9], written down before the EPR paper, the density matrix becomes real. Physically observable quantities require smearing the Wigner function over an area in the phase space (with the characteristic scale $\Delta x \Delta p \sim h$), which wipes out locally negative weights and restores positivity of observed probabilities. How such a density matrix would arise in quantum mechanics, and the dynamics of what really happens during quantum measurement, remain open questions for a different level of analysis.

It must be emphasized that negative weights in the analysis of a physical problem are not an obstacle of principle. As an example, consider the diffusion equation describing evolution of temperature over a region. It is routinely solved by decomposing the temperature into its Fourier eigenmodes and then determining the contribution of each eigenmode. By definition, the Fourier eigenmodes are sinusoidal functions giving both positive and negative contributions. On the other hand, the temperature that is the sum of all Fourier eigenmodes is always positive. There is no conflict of any kind, and the important lesson is that physical reality should not be demanded of mathematical variables.

Where does all this leave us? While it is certainly worthwhile to keep on contemplating about foundational questions and interpretation of quantum mechanics, it is best to follow Mermin's advice for practical applications of quantum mechanics: 'Shut up and calculate!' In fact, the Physics Breakthrough Prize for 2022 was awarded to Charles H. Bennett, Gilles Brassard, David Deutsch and Peter Shor 'for foundational work in the field of quantum information'[10]. They have used the well-established features of quantum theory to direct progress in the rapidly upcoming field of quantum technology.


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