The Experiments That Led to the Nobel Prize in Physics 2022*

Urbasi Sinha

The Nobel Prize in Physics 2022 has been awarded to John F. Clauser, Alain Aspect, and Anton Zeilinger, with each sharing 1/3rd of the prize. The prize has been awarded for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science. In this article, we aim to understand the physics and technologies behind the experiments that led to the prize. While each experimental contribution is seminal, we attempt to understand what makes them different from each other, what makes each of them unique, and how they have led to the burgeoning field of quantum science and technologies.

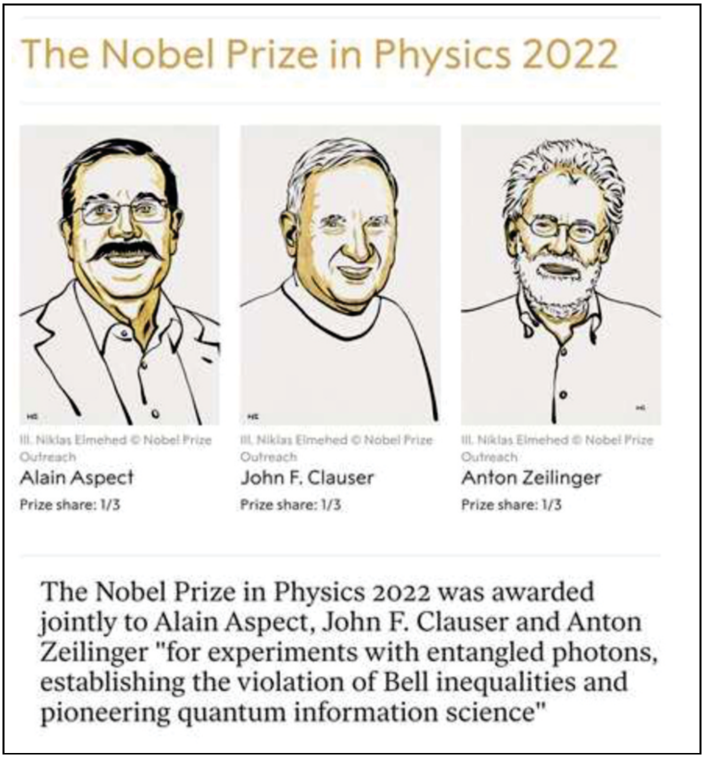
Urbasi Sinha is a Professor at RRI Bangalore, where she heads the Quantum Information and Computing (QuIC) laboratory. She is a Simons Emmy Noether Fellow at the Perimeter Institute, Canada, and an associate faculty member at IQC, University of Waterloo, Canada, and CQIQC, University of Toronto, Canada. QuIC lab specializes in experiments on photonic quantum information processing, including quantum computing and quantum communication, primarily using single and entangled photons, and is leading India's first project on satellite-based secure quantum communications.

1. Introduction

This year's prize is specifically important to me for two specific reasons. The first reason is a personal one, as the prize has been awarded in the field of photonic quantum information, which is what I and my lab members from the Quantum Information and Computing (QuIC) lab at the Raman Research Institute, Bengaluru, are specifically engaged in. This prize is thus very special for us as well as the entire photonic quantum science and technologies community. I think the entire community unanimously will agree that the prize, in fact, is long overdue, and we are thrilled that it has finally happened this year! The second reason for its specific importance lies in the citation. While many Nobel Prizes have been awarded for fundamental science discoveries, this prize recognises not just the seminal fundamental science contributions of the Nobel laureates for experiments with entan-

---

*Vol.28, No.1, DOI: https://doi.org/10.1007/s12045-023-1528-1



The Nobel Prize in Physics 2022

Ill. Niklas Elmehed © Nobel Prize Outreach
Alain Aspect
Prize share: 1/3

Ill. Niklas Elmehed © Nobel Prize Outreach
John F. Clauser
Prize share: 1/3

Ill. Niklas Elmehed © Nobel Prize Outreach
Anton Zeilinger
Prize share: 1/3

The Nobel Prize in Physics 2022 was awarded jointly 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"

Figure 1. The Nobel Prize in Physics 2022 citation (https://www.nobelprize.org/prizes/physics/2022/summary/).

Keywords
Nobel prize, entanglement, locality, realism, quantum information, quantum mechanics, quantum technology, Bell's inequality, entangled photons.

gled photons and establishing the violation of Bell inequalities. It also recognizes the tremendous technological ramifications of these experiments by also awarding it towards pioneering quantum information science. Thus, the prize is awarded for both the science and the technology, which is, in fact, a fitting ode to the entire field of quantum information science that represents the symbiotic relationship between fundamental science and applied technologies. *Figure* 1 depicts the citation for the Nobel Prize in Physics 2022.

While the article intends to describe holistically the work that led to the Nobel Prize, I would like to begin with a disclaimer. The topics that are spanned by this year's prize can sometimes lend themselves to philosophical/non-technical expositions. However, we note that this year's prize is, in fact, for the experiments. As an experimentalist, I will stick to the details of these experiments and why each of them is an integral component in the Nobel story and not digress towards interpretational issues.

Before we go on to understand and appreciate the experiments, let us recap some of the key physics concepts that we need to know to enable such an understanding. In this article, I will not discuss details of these concepts (which are very well covered in the vast literature that each of them enjoys) but give you a flavour of what they entail so that the importance of the experiments comes through.

The three key concepts are—*entanglement*, *locality*, and *realism*.

Entanglement

To talk about entanglement, let us briefly review the concept of the wave function. In Dirac's 'bra-ket' notation, we denote this by $|\psi\rangle$. In position space, the wave function of a particle depends on the space coordinates as well as time and also other quantum numbers like mass and spin. The quantum labels correspond to the eigenvalues of commuting observables, and in general, the wave function is a superposition of eigenfunctions of these observables. The absolute square of the wave function gives the probability of finding a particle at a given space-time coordinate. Mathematically, the wave function belongs to a special type of vector space called Hilbert space, endowed with a finite inner product. We can consider the wave function of a joint system, say of two particles, called a bipartite system. If the resulting wave function is a direct product of the wave function of the individual particles, then we say that the system is not entangled.

A bipartite system is said to be entangled if it cannot be written as a direct product of two states from the two subsystem Hilbert spaces.

A bipartite system is said to be entangled if it cannot be written as a direct product of two states from the two subsystem Hilbert spaces [1].

For instance, for pure entangled states:

$$|\psi\rangle_{AB} \neq |\psi\rangle_A \otimes |\psi\rangle_B.$$

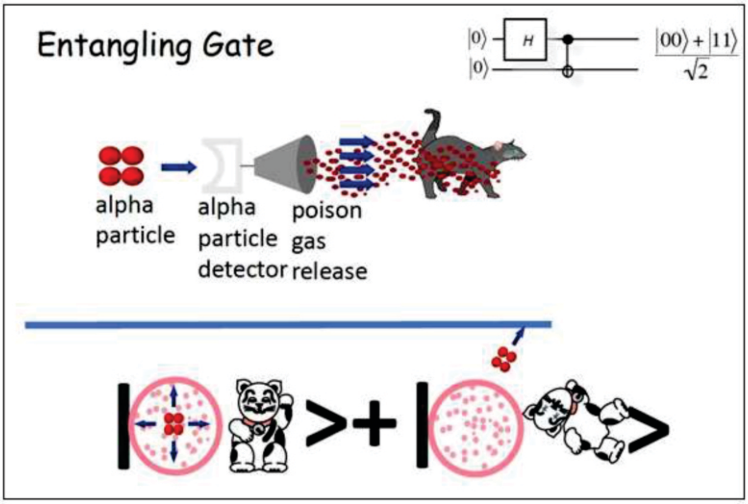


Figure 2. The circuit on top discusses the mathematical way of generating entanglement, which involves applying a Hadamard gate to the first input qubit followed by a CNOT on both. When the cat is inside the box, and the radioactive particle has not decayed, the cat does not have the poison and lives. If the radioactive particle does decay, this leads to the cat having the poison, and it dies. Thus, the state of the cat is entangled with that of the radioactive particle. (Picture courtesy: Barry C Sanders, University of Calgary, Canada).

Bell states are examples of maximally entangled states and form a complete basis.

$$|\phi\rangle_{\pm} = \frac{1}{\sqrt{2}}(|00\rangle \pm |11\rangle), \quad |\psi\rangle_{\pm} = \frac{1}{\sqrt{2}}(|01\rangle \pm |10\rangle).$$

In order to understand this in a slightly non-technical but accurate way, we recall the Schrödinger cat thought experiment [2]. There is a cat inside an opaque box. A vial of poison accompanies the cat. If the cat has the poison, it dies; if it does not, it lives. As an observer outside the box, we do not know apriori whether the cat has had the poison or not. Thus, for the external observer, the cat is in a ‘superposition’ of being dead and alive (till we open the box). Opening the box and looking is not an option in this thought experiment. We need some other means of knowing the state of the cat. This brings us to the third element in the thought experiment. Along with the cat and the vial of poison, we also now include a radioactive particle in the box, the condition being that if the radioactive particle does not decay, the cat does not have the poison and lives. On the other hand, if the radioactive particle does decay, the cat has the poison and dies. Thus, the state of the cat is now ‘tagged’ by the radioactive particle. If the particle has

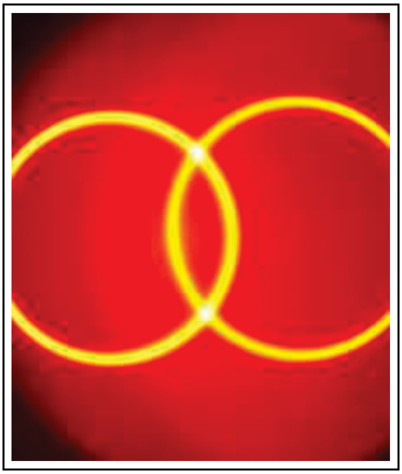


Figure 3. Type II SPDC rings from an entangled photon source in the Quantum Information and Computing lab, RRI Bengaluru, India.

not decayed, we know that the cat is alive, whereas if the particle is emitted, we know that the cat is dead. In other words, the state of the cat is 'entangled' with the state of the radioactive particle.

Figure 2 describes this through an illustration.

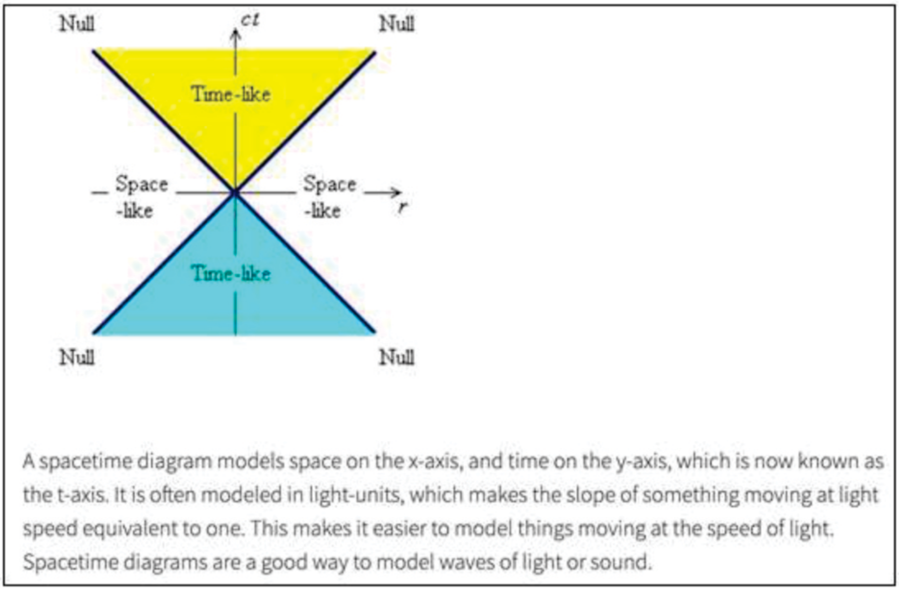
Figure 3 is a picture of entangled photons from the QuIC lab. The image has been taken using a highly sensitive camera. Spontaneous parametric down-conversion (SPDC) is a standard non-linear optics technique for generating entangled photons. The photons are generated in the form of cones, the cross-section of the cones on a plane being circles. The left cone contains the horizontally polarised photons, while the right cone contains the vertically polarised photons. However, at the point of intersection between the two cones, there is ambiguity. If the first photon comes from the left cone, the second comes from the right and vice versa. However, apriori we do not know which cone the photons belong to, and this thus describes an entangled state:

$$|HV\rangle \pm |VH\rangle.$$

Spontaneous parametric down-conversion (SPDC) is a standard non-linear optics technique for generating entangled photons.

Locality

Figure 4 illustrates what is called a spacetime diagram [3]. According to Einstein's separability criterion, or the special relativis-



A spacetime diagram models space on the x-axis, and time on the y-axis, which is now known as the t-axis. It is often modeled in light-units, which makes the slope of something moving at light speed equivalent to one. This makes it easier to model things moving at the speed of light. Spacetime diagrams are a good way to model waves of light or sound.

Figure 4. A spacetime diagram (https://girlstalkmath.com/2017/06/30/special-relativity/).

tic locality, two events within the light cone are called timelike separated. Events on the boundary of the light cone are lightlike separated, whereas two events, one of which is within the light cone and the other outside the light cone, are spacelike separated. Spacelike separated events require faster than the speed of light communication. Thus, if two events are non-local according to Einstein's separability criterion, they need to be inside and outside the light cone, respectively. However, we will realise as we move along that John Bell's locality assumption was stronger than this.

There has been some confusion in the literature regarding the compatibility of Einstein's special relativity with quantum mechanics.

There has been some confusion in the literature regarding the compatibility of Einstein's special relativity with quantum mechanics. The general consensus is that there is no incompatibility since, despite the nonlocal quantum correlations, there is never any faster-than-light communication. Any potential communication is always via a classical channel, where the entity used in communication travels at a velocity less than or equal to that of light. One way to understand how Bell's locality assumption differs from the special relativistic locality was expounded in the literature in an article by Ballentine and Jarrett [4]. To understand what Ballentine and Jarrett talk about, we need to introduce the concept of joint probabilities. In the discussion of Bell's inequalities, we typically have multiple parties, with each party having the capability of choosing to measure from a set of different observables. For simplicity, let us assume two parties, Alice and Bob, each being able to make two different measurements. Joint probabilities are defined as the probability of Alice getting a specific outcome when making her measurement and Bob getting a specific outcome when making his measurement.

Ballentine and Jarrett argue that the locality assumption going into the derivation of Bell's inequalities is a combination of special relativistic locality (which was dubbed as 'simple locality' by them) and another nontrivial criterion called predictive completeness. Special relativistic locality can be explained as follows. Suppose the spacetime events where Alice and Bob make measurements are space-like separated. This means that their spacetime events (the act of measurement at a particular time and space) are outside each other's light cone. Then, the probabilities that Alice measures on performing her set of measurements should be independent of whether Bob makes any measurement. Mathematically, we get a condition that states that the probabilities observed by Alice when Bob makes no measurement is equal to the sum over all the outcomes of Bob's measurements in their joint probabilities. Similarly, we get a condition for Bob's observed probabilities. The assumption, which Ballentine and Jarrett dub as 'strong locality', that goes into the derivation of Bell's inequalities states that the joint probabilities are a product of the individual probabilities referred to above. The latter (strong locality) implies the former (special relativistic locality). However, the converse is not true. To make the converse true, one gets a condition that is dubbed 'predictive completeness'. In words, this condition relates the joint probabilities to the product of the sum of joint probabilities, where the first sum is over Alice's outcomes and the second sum is over Bob's outcomes. This condition does not automatically hold. The failure of Bell's condition is due to the failure of predictive completeness and not due to the failure

> Ballentine and Jarrett argue that the locality assumption going into the derivation of Bell's inequalities is a combination of special relativistic locality (which was dubbed as 'simple locality' by them) and another nontrivial criterion called predictive completeness.

of special relativistic locality.

Einstein, Podolsky and Rosen argued that quantum mechanics needs to be completed, presumably by introducing hidden variables [5]. Ballentine and Jarrett argue that this incompleteness that EPR talk about implies the failure of predictive completeness. There has been some debate about this interpretation in the literature, but we will refrain from going into this debate here.

Realism

What do the non-classical features of quantum mechanics reveal about the nature of reality?

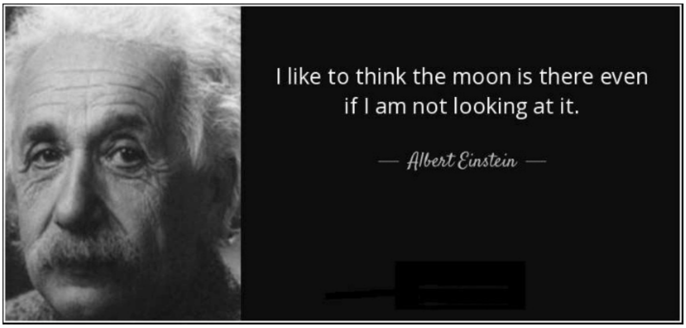
A question that often plagues many of us would surely be, "What do the non-classical features of quantum mechanics reveal about the nature of reality?" How to reconcile our everyday experience of the macroscopic world with the 'weird' behaviour of the microphysical world described by QM? Indeed, we find that many of the principles that are natural in the quantum domain do not necessarily manifest themselves in the macroscopic domain, and one of the longstanding research goals of the community has been to probe what is called the quantum-classical limit.

The classical realist worldview states that a system is in a definite state for which all its observable properties have definite values independent of measurement.

This brings us to yet another concept that indeed sees very different manifestations in the quantum world. This concept is called 'realism'. The classical realist worldview states that a system is in a definite state for which all its observable properties have definite values independent of measurement [6]. Unlike a classical state, the specification of a quantum state does not, in general, give the values of dynamical variables possessed by a system. Thus, a dynamical variable is generally taken to have no definite measurement-independent value.

In other words, measurement according to quantum mechanics, in general, does not reveal a pre-existent value of a dynamical variable.

To illustrate this through an example: Consider the tree that may be right outside your window. The tree will continue being outside the window, regardless of whether or not you are looking at it. The act of 'looking' is the measurement here. Thus, irre-



[redacted]

Figure 5. This is a famous quote attributed to Einstein [7].

spective of the measurement, the tree's position remains invariant. However, this is not the case for a quantum state. A quantum state does not have a property independent of measurement. Only by measuring one reveals a certain dynamical variable or property. This is indeed a counterintuitive notion for our 'classical' way of thinking and these puzzled great minds, including, for instance, Albert Einstein. *Figure* 5 depicts a quote that is attributed to Einstein, which exemplifies this puzzle.

It is with the assumption of locality and realism that John Stewart Bell came up with what are now called Bell inequalities [8]. This is a set of inequality conditions that are respected by systems which agree with local realism. These inequalities are violated by systems that violate local realism. This year's Nobel Prize has been given for such seminal experiments, which show the violation of Bell inequalities and thus provide a strong violation of local realism.

Bell inequalities is a set of inequality conditions that are respected by systems which agree with local realism. These inequalities are violated by systems that violate local realism.

We now go on to show a simple derivation of a certain form of the Bell inequalities. As we will see, the assumptions of locality and realism play a critical role in deriving the same.

Consider two parties, Alice (A) and Bob (B).

Alice chooses to perform one of 2 possible measurements A_0 or A_1. These are binary measurements. Likewise, Bob chooses between two binary measurements, B_0 or B_1. Result of $\mathrm{A}_0 = +1$ or -1 Likewise, Result of $\mathrm{A}_1 = +1$ or -1.

ASSUMPTIONS: Each measurement revealed a property that

the particle already possessed independent of being observed/ measured (realism), and Alice's choice of action cannot influence Bob's result or vice versa (locality).

Example: Alice chooses to measure A$_0$ and obtains the result +1, then the particle she received carried the value of +1 for a property a$_0$.

Consider the following combination:

$$a_0b_0 + a_0b_1 + a_1b_0 - a_1b_1 = (a_0 + a_1)b_0 + (a_0 - a_1)b_1. \qquad (1)$$

Now, either $a_0 = a1$ or $a_0 = -a1$ [Recall, $a_0 = +/-1, a_1 = +/-1$]

From (1), either $(a_0 + a_1)$ will be 0 or $(a_0 - a_1)$ will be 0. The other term will then evaluate to +/− 2. The experiment is repeated over many trials with new pairs of particles. The average over many trials for the combination $a_0b_0 + a_0b_1 + a_1b_0 - a_1b_1$ will be <= 2.

No single trial can measure the quantity because Alice and Bob choose one measurement each at a time. But, on the assumption that underlying properties exist, Average of sum = Sum of averages:

$$\Rightarrow \langle A_0B_0\rangle + \langle A_0B_1\rangle + \langle A_1B_0\rangle - \langle A_1B_1\rangle \leq 2. \qquad (2)$$

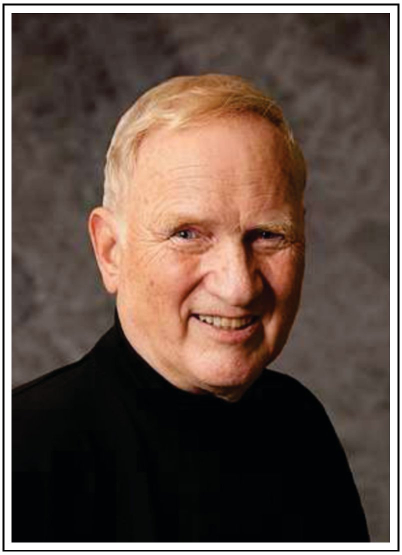
This is called the **CHSH form of the Bell inequality** and was derived by John F. Clauser, Michael Horne, Abner Shimony and Richard Holt [9].

What Happens in Quantum Mechanics?

Consider a Bell state $|\psi\rangle = \frac{|01-|10\rangle}{\sqrt{2}}$.

Let Alice's measurements be $A_0 = s_x$ and $A_1 = s_z$.

Likewise, Bob's measurements are $B_0 = -(s_x + s_z)/\sqrt{2}$ and $B_1 = (s_x - s_z)/\sqrt{2}$. Then, quantum expectation values of pairs of these observables using Born's rule will be:



John F. Clauser: Nobel Laureate in Physics 2022.

$$\langle A_0B_0\rangle = 1/\sqrt{2}, \langle A_0B_1\rangle = 1/\sqrt{2}, \langle A_1B_0\rangle = 1/\sqrt{2} \text{ and } \langle A_1B_1\rangle = -1/\sqrt{2},$$

$$\Rightarrow \langle A_0B_0\rangle + \langle A_0B_1\rangle + \langle A_1B_0\rangle - \langle A_1B_1\rangle = 2\sqrt{2}. \qquad (3)$$

This is the famous Tsirelson's bound [10]. The LHS of equation (3) is called the Bell parameter 'S'. From equations (2) and (3), it follows that experiments that satisfy local realism will follow (2), and the Bell parameter will be measured to be less than or equal to 2. For experiments that violate Bell inequalities, S will be measured to be greater than 2, the maximum possible value being $2\sqrt{2}$.

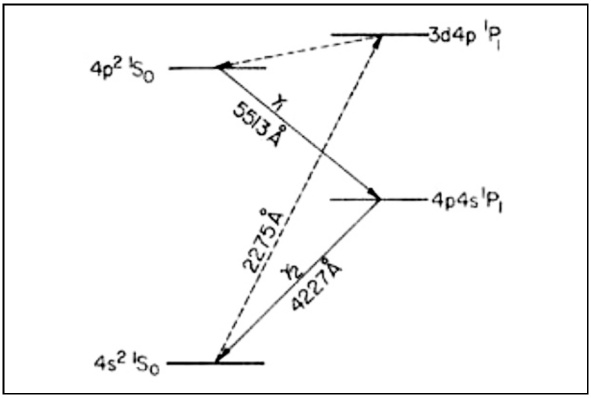
For experiments that violate Bell inequalities, S will be measured to be greater than 2, the maximum possible value being $2\sqrt{2}$.

With this introduction to the key concepts, we now go on to discuss the experiments that led to the Nobel Prize in Physics 2022. All of them show a strong violation of the Bell inequalities and, in effect, local realism.

Experiments That Led to the Nobel Prize in Physics 2022

First, we discuss the work of John F. Clauser. John F. Clauser was an astrophysicist by training. While doing his PhD, he developed

Figure 6. The level scheme of calcium. Dashed lines show the route for excitation to the initial state 4p^2 ^{1}S$_0$. Resonance absorption of 2275Å photons excited the calcium atoms to the 3d4p^{1}P$_1$ state. Of the atoms that did not decay directly to the ground state, about 7% decayed to the 4p^2 ^{1}S$_0$ state, from which they cascaded through the 4s4p^{1}P$_1$ intermediate state to the ground state with the emission of two photons at 5513Å and 4227Å. Adapted with permission from S. J. Freedman and J. F. Clauser, *Phys. Rev. Lett.*, Vol.28, No.14, pp.938–941, 1972. [11]



a deep interest in the foundations of quantum mechanics. He was also aware that there was a setup developed by Commins and his Phd student Kocher at the University of California, Berkeley, that could produce a pair of correlated photons using a calcium atom cascade. He wanted to do a Bell inequality experiment using this setup. He thus joined the University of California, Berkeley as a postdoctoral fellow. However, the catch was that his postdoc mentor was Charles Townes, a renowned radio astronomer who wanted Clauser to work on radioastronomy for his postdoctoral work. Clauser, on the other hand, had his mind set on working on a Bell violation experiment! He managed to convince Townes of the importance of such an experiment, and Townes, in turn, struck a deal with Commins. The deal was that Clauser would work with Commins' calcium setup for fifty per cent of his time along with Commins' then PhD student Stuart Freedman. This collaboration between Clauser and Freedman led to the first-ever experiment on Bell inequality violation [11]. The rest, as they say, is history!

As with most first experiments, this, too, was based on several simplistic assumptions, which were removed by later, more sophisticated experiments. The calcium atom cascade that was used to generate the two photons is described in *Figure* 6.

The assumptions included the following:

- The two photons propagate as separated localized particles.
- A binary selection process occurs for each photon at each polar-

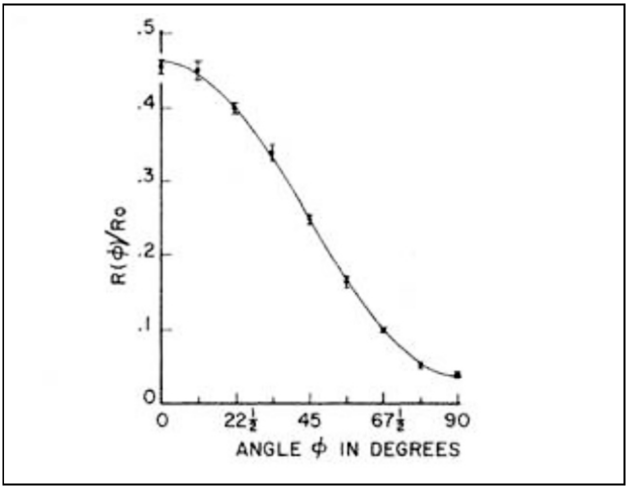


Figure 7. Coincidence rate with angle ϕ between the polarizers, divided by the rate with both polarizers removed, plotted versus the angle ϕ. The solid line is the prediction of quantum mechanics, calculated using the measured efficiencies of the polarizers and solid angles of the experiment. Adapted with permission from S. J. Freedman and J. F. Clauser, *Phys. Rev. Lett.*, Vol.28, No.14, pp.938–941, 1972. [11]

izer (transmission or no transmission). The selection does not depend on the orientation of the distant polarizer.

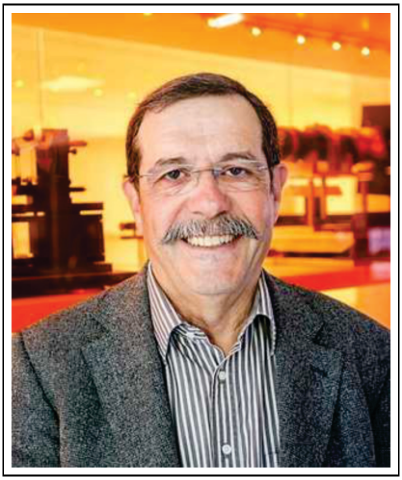
- All photons incident on a detector has a probability of detection independent of whether or not the photon has passed through a polarizer.

One of the main experimental ingenuities was the use of a special type of polarizer. The requirement for large efficient linear polarizers led them to employ ‘pile-of-plates’ polarizers. Each polarizer consisted of ten 0.3 mm thick glass sheets inclined nearly at Brewster’s angle. This greatly increased the efficiency of the experiment. The Bell inequality they worked with was of the same form as the original Bell work and is included below.

$$\delta = \left|R\left(22\frac{1^{\circ}}{2}\right)/R_0 - R\left(67\frac{1^{\circ}}{2}\right)/R_0\right| - \frac{1}{4} \leq 0.$$

The cycling and averaging procedure minimized the effects of drift and apparatus asymmetry. The results of the measurements of the correlation $R(\phi)/R_0$ corresponding to a total integration time of ~200 hours are shown in *Figure* 7.

All error limits are conservative estimates of 1 standard deviation. Using the values of 22.5 degrees and 67.5 degrees, they obtain



Alain Aspect: Nobel Laureate in Physics 2022.

$\delta = 0.050 + / - 0.008$ in clear violation of the above inequality. Furthermore, no evidence for a deviation from the predictions of QM, calculated from the measured polarizer efficiencies and solid angles, is observed. This thus provides strong evidence against local hidden-variable theories.

On to the Contributions of the Second Nobel Laureate, Alain Aspect

The first experiment in any domain is usually not the most precise or foolproof. Its importance lies in demonstrating that something is possible for the first time. Alain Aspect's contributions to the Nobel Prize lie in coming up with more and more rigorous experiments with an increasingly smaller number of loopholes. Three of his experiments with collaborators primarily contribute towards the prize, with the last one managing to close many major loopholes. So, what is a loophole? According to the formal definition: It is an ambiguity or an inadequacy in the law or a set of rules. It is used in the same manner in Bell inequality violation experiments as well. If the experiment is not assumption-free, then there is always an ambiguity about the conclusion. To take a popular example of a loophole that plagues all quantum optics

The first experiment in any domain is usually not the most precise or foolproof. Its importance lies in demonstrating that something is possible for the first time.

experiments, let us understand the detection efficiency loophole. When photons, or any other particle for that matter, are incident on a detector, all photons are not detected. That is because no detector has 100% efficiency. If a detector has 60% efficiency, say, only 60 out of the 100 photons that are incident on it will be detected. Going forward, these photons may violate Bell inequalities. But what about the 40 photons that are not detected? They may or may not violate the inequality. We cannot comment on what they may do as we do not measure them. Thus even if the photons that are detected do violate the inequality, there are some photons that are not detected that may or may not do so. This leads to ambiguity in the conclusion of the experiment. This detection efficiency loophole thus prevents a completely convincing and ambiguity-free violation of the Bell inequalities. Likewise, there were many other loopholes in the first Bell inequality experiments. If these loopholes are not closed, the experimental conclusions would remain ambiguous. Alain Aspect and his collaborators contributed to the systematic closure of many of these loopholes through their series of experiments.

The first Aspect experiment [12] was also based on a calcium cascade, like the Clauser experiment. The only difference being instead of using resonance absorption, they selectively pumped the calcium atoms to the upper level of the cascade from the ground state by two-photon absorption.

The first Aspect experiment was also based on a calcium cascade, like the Clauser experiment. The only difference being instead of using resonance absorption, they selectively pumped the calcium atoms to the upper level of the cascade from the ground state by two-photon absorption.

The measurement setup was also similar to the Clauser experiment and is shown in *Figure* 8.

The same Bell inequality was measured as the one in the Clauser experiment. The measured value was $\delta_{\text{exp}} = 5.72 \times 10^{-2} + / - 0.43 \times 10^{-2}$, violating the inequality by more than 13 standard deviations and in perfect agreement with the QM prediction of $\delta_{\text{QM}} = 5.8 \times 10^{-2} + / - 0.2 \times 10^{-2}$.

An important ingenuity in this experiment was the study of the effect of moving the polarizers away from the source. Moving each polarizer 6.5 m away from the source, i.e., to four coherence lengths of the wave packet associated with the lifetime of the in-

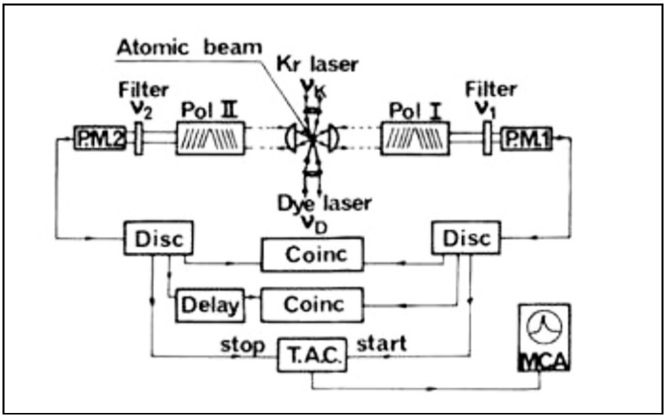


Figure 8. The schematic of the apparatus and electronics. Laser beams are focused onto the atomic beam perpendicular to the figure. The fluorescence signals generate feedback loops that control the krypton laser power and the dye-laser wavelength. There are discriminator feed counters as well as coincidence circuits. The MCA (multichannel analyser) displays the time-delay spectrum. Adapted with permission from Aspect et al., *Phys. Rev. Lett.*, Vol.47, No.7, pp.460–463, 1981. [12]

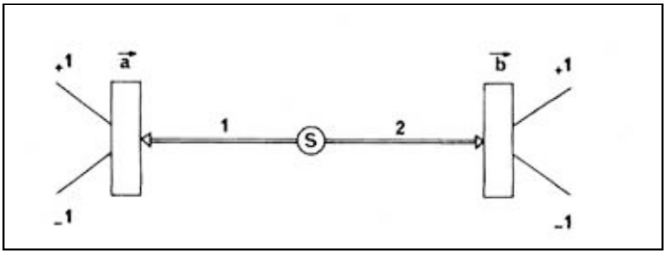


Figure 9. The Einstein–Podolsky–Rosen–Bohm (EPR–Bohm) *gedanken-experiment.* Two spin-1/2 particles (or photons) in a singlet state or similar state are separated and sent to two different measurement stations. The spin components (or linear polarisations) of 1 and 2 are measured along **a** and **b**. Strong correlations are predicted between these two measurements by quantum mechanics. Adapted with permission from Aspect et al., *Phys. Rev. Lett.*, Vol.49, No.2, pp.91–93, 1982. [13]

termediate state of the cascade (5 ns), no change in results was observed. The results were in excellent agreement with quantum mechanics predictions and, to a high statistical accuracy, a strong evidence against the whole class of realistic local theories. **No effect of distance between measurements on the correlations was observed.**

The second Aspect experiment [13] was an important advancement due to many reasons. The schematic for the original EPR–Bohm *gedankenexperiment* is shown in *Figure* 9.

In such a setup:

$$E(\vec{a},\vec{b}) = P_{++}(\vec{a},\vec{b}) + P_{--}(\vec{a},\vec{b}) - P_{+-}(\vec{a},\vec{b}) - P_{-+}(\vec{a},\vec{b})$$

$$-2 \leq S \leq 2,$$

here,

$$S = E(\vec{a},\vec{b}) - E(\vec{a},\vec{b'}), + E(\vec{a'},\vec{b}) + E(\vec{a'},\vec{b'}).$$

Experiments till then, including his own, did not follow the scheme of *Figure* 9 closely enough. Some experiments were performed with pairs of low-energy photons emitted in atomic radiative cascades. True polarizers were available in the visible range. All previous experiments involved single-channel analyzers, transmitting one polarization and blocking the orthogonal. The measured quantities were thus only the coincidence rates in +1 channels: R_{++} **(a, b)**.

The low efficiency of detection systems (PMTs have low efficiency and angular acceptance is small) implies that measurements of polarizations were inherently incomplete. If no count is obtained at the PMT, it could be because of low detector efficiency or because it has been blocked by a polarizer. The latter is the real polarization measurement. **R_{+-} (a, b)** or **R_{--} (a, b) could not be measured directly.** Auxiliary measurements were required where coincidence rates are measured with one or both polarizers removed. One could then obtain operational inequalities with further assumptions.

This brings us to the experimental ingenuities of the second Aspect experiment [13].

The experiment followed much more closely the EPR *gedanken-experiment* compared to all previous experiments. True dichotomic polarization measurements on visible photons were performed by replacing polarizers with two-channel polarizers, separating two orthogonal linear polarizations, followed by two PMTs. (**Polarizing beam splitters are thus introduced into Bell inequality experiments!**). Each polarizer was mounted in a rotatable mechanism holding two PMTs. This ensemble is called a polarimeter. This makes it very similar to the usual Stern–Gerlach measurements for spin-1/2 particles. *Figure* 10 shows the experimental schematic. Moreover, **four-fold coincidence technique** was used, and the **four coincidence rates R_{++} (a, b), R_{+-} (a, b), R_{-+}**

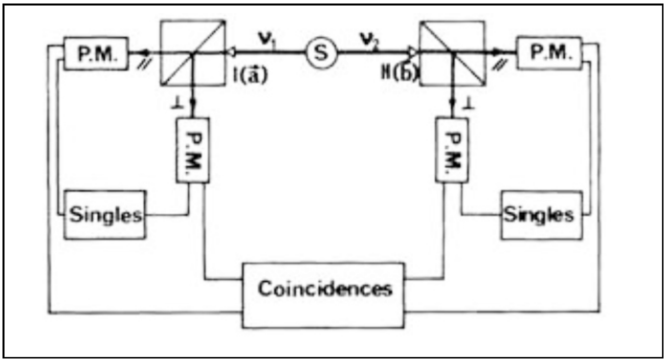


Figure 10. The schematic of the experiment. Two polarimeters, I and II, in orientations a and b, perform true dichotomic measurements of linear polarization on two photons. Each polarimeter is rotatable around the axis of the incident beam. The counting electronics monitors the singles and the coincidences. Adapted with permission from Aspect et al., *Phys. Rev. Lett.*, Vol.49, No.2, pp.91–93, 1982. [13]

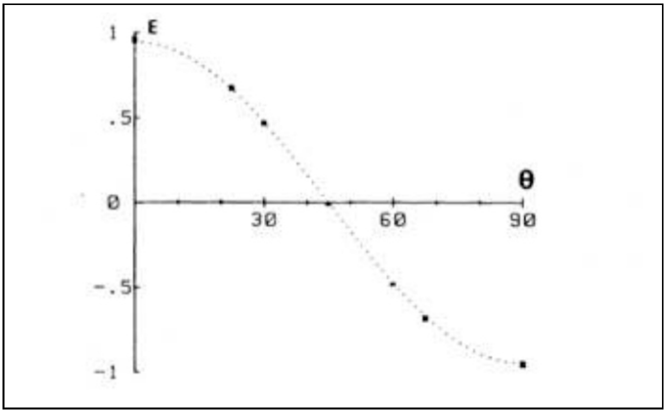


Figure 11. Plot for the correlation of polarizations as a function of the relative angle of the polarimeters. The indicated errors are +/− 2 standard deviations. The dotted curve is the quantum mechanical prediction for the actual experiment. For ideal polarizers, the curve would reach the values +/−1. Adapted with permission from Aspect et al., *Phys. Rev. Lett.*, Vol.49, No.2, pp.91–93, 1982. [13]

(a, b), R_{--} (a, b) were all measured in a single run! .

The quantity being measured was:

$$E(\vec{a}\vec{b}) = \frac{R_{++}(\vec{a}\vec{b}) + R_{--}(\vec{a}\vec{b}) - R_{+-}(\vec{a}\vec{b}) - R_{-+}(\vec{a}, b)}{R_{++}(\vec{a}, b) + R_{--}(\vec{a}, b) - R_{+-}(\vec{a}, b) - R_{-+}(\vec{a}, b)}.$$

Thus, the experiment was repeated for three other choices of orientations and the earlier S parameter was used directly as a test of local realism.

Figure 11 shows the experimental result.

For settings at maximum violation, S_{exp} = 2.697 +/- 0.015 with the QM prediction being S_{QM} = 2.70 +/- 0.05.

This was the strongest violation of Bell's inequalities achieved till then and demonstrated excellent agreement with QM. The experiment presented straightforward transpositions of the ideal EPR scheme; the procedure was simple and needed no auxiliary measurements, unlike previous experiments.

At this point, one may be tempted to think that there is not much left to do. However, that is quite far from reality!

While this was indeed a seminal experiment, caveats still remained.

The assumption is that the ensemble of actually detected pairs is a faithful sample of all emitted pairs. This is an assumption as it is not necessarily true. because of inefficient detectors, not all emitted pairs are actually detected. While care was taken to ensure that the conditions were similar in different runs of the experiment, this still remained a loophole. Thus two main loopholes remained at this stage:

- The above **detection efficiency/fair sampling loophole.**
- The **static character** of all previous experiments (freedom of choice loophole).

The third Aspect experiment [14] closed the latter, i.e., the freedom of choice loophole.

All experiments, so far, had been performed with static setups in which polarizers are held fixed for the whole duration of time. As discussed earlier in the article, Bell's strong locality condition entails not only the Einsteinian separability criterion but also an additional assumption that prevents the result of the measurement on one party from being affected by the measurement setting on the other party. In the situation involving entangled photons and polarization measurements, this would mean that the results of the measurement of polarizer II do not depend on the orientation of polarizer I and vice versa, nor does the way in which pairs are emitted depend on a or b. This may be reasonable, but such a locality condition is not prescribed by any fundamental law. Bell himself points out: "The settings of the instruments are made sufficiently in advance to allow them to reach some mutual rapport

Bell's strong locality condition entails not only the Einsteinian separability criterion but also an additional assumption that prevents the result of the measurement on one party from being affected by the measurement setting on the other party.

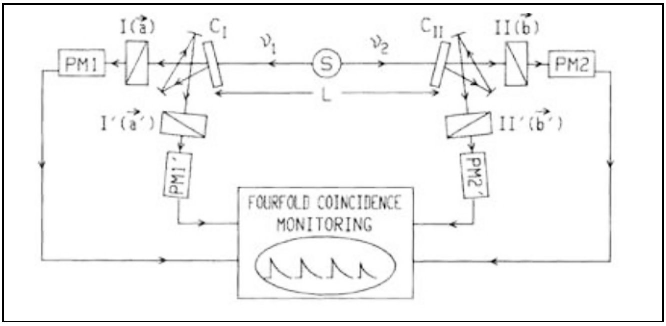


Figure 12. The ingenuity in the experiment was the use of optical switches. The switching device (CI, CII) is followed by two polarizers in two different orientations. The combination of the switching device and polarizer is equivalent to a polarizer switched fast between two orientations. Adapted with permission from A. Aspect et al., *Phys. Rev. Lett.*, Vol.49, No.5, pp.1804–1807, 1982. [14]

by exchange of signals with velocity less than or equal to that of light”. Essentially, the two parties could decide to have some prior interactions and develop a recipe for measurement settings to be employed. If such interactions existed, Bell’s locality condition would no longer hold for static experiments, nor would Bell’s inequalities! Bell thus insisted on the importance of experiments in which settings are changed during the flight of the particles. **The current Aspect paper reports the results of the first experiment using variable polarizers** [14].

Aspect proposed how to do such a measurement in an earlier work [15]. Essentially, it involves the usage of innovative optical switches to switch the polarization setting after the particles have started their journey from the source to the measurement stations.

Figure 12 shows a schematic of the experimental setup, and *Figure* 13 shows the mechanism of the optical switch.

The switching between the two channels occurs about each 10 ns. This delay, as well as the lifetime of the intermediate level of the cascade (5 ns), is small compared to L/c, which is 40 ns. Thus, a detection event on one side and the corresponding change of orientation on the other side are separated by a spacelike interval. *Figure* 14 shows the results of the experiment.

The new feature of this experiment was that the settings of the polarizers are changed at a rate greater than c/L. However, the ideal scheme is not completed since the change is not truly random but rather quasiperiodic. The switches on the two sides were driven by different generators at different frequencies. Thus it was natu-

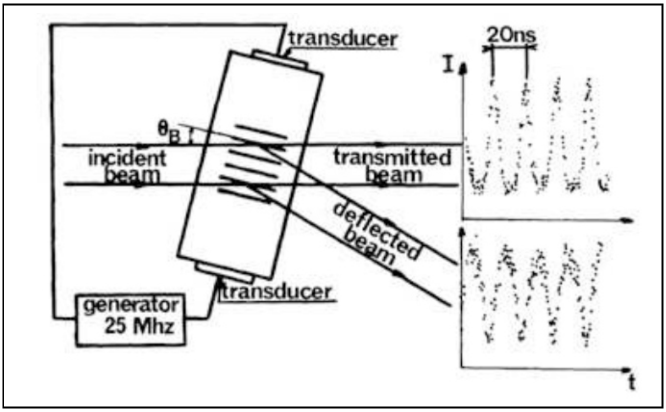


Figure 13. This shows the workings of the optical switch. The incident light is switched at a frequency of around 50 MHz by diffraction at the Bragg angle on an ultrasonic standing wave. The transmitted and deflected beam intensities have been measured as a function of time with the actual source. The fraction of light deflected towards other diffraction orders is negligible. Adapted with permission from A. Aspect et al., *Phys. Rev. Lett.*, Vol.49, No.5, pp.1804–1807, 1982. [14]

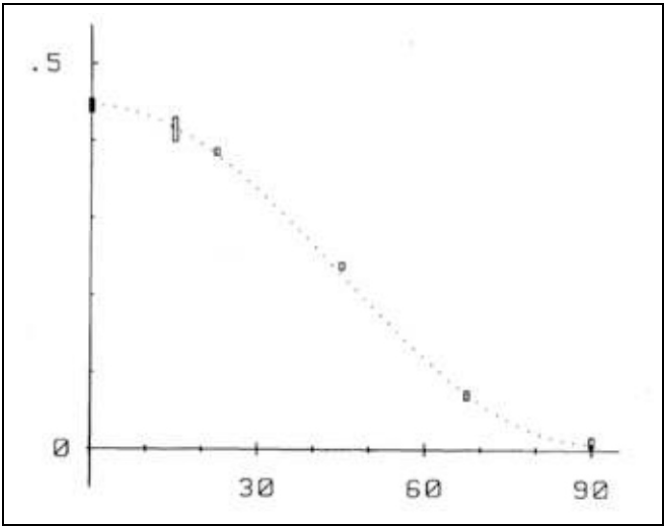
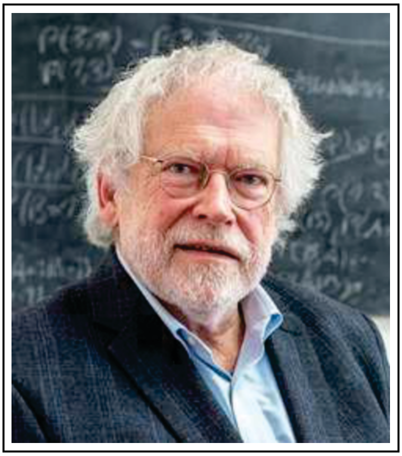


Figure 14. The averaged normalised coincidence rate as a function of the relative orientation of the polarizers. The errors indicated are the +/− 1 standard deviation. The dashed curve is the quantum mechanical prediction for the actual experiment. Adapted with permission from A. Aspect et al., *Phys. Rev. Lett.*, Vol.49, No.5, pp.1804–1807, 1982. [14]

ral to assume that they function in an uncorrelated way. A more ideal experiment with random and complete switching would be necessary for a fully conclusive argument. The next work reports this ideal experiment and also marks the first seminal contribution from the third Nobel laureate, Anton Zeilinger, to the Nobel Prize in Physics 2022.

The **first Zeilinger experiment** [16] that contributed to the Nobel Prize in Physics 2022 was, in fact, the ideal experiment that we just discussed the need for. Zeilinger and his collaborators



Anton Zeilinger: Nobel Laureate in Physics 2022.

The first Zeilinger experiment that contributed to the Nobel Prize in Physics 2022 was, in fact, the ideal experiment.

performed an experiment where the necessary spacelike separation of the observations was achieved by the sufficient physical distance between the measurement stations, by the ultrafast and random setting of the analyzers and by completely independent data registration. The third Aspect experiment had used periodic sinusoidal switching, which can be predictable into the future. Here, communication slower than the speed of light or even at the speed of light could, in principle, explain the results obtained. Thus, the locality loophole still remains open.

So, What is Needed to Close the Locality Loophole Unambiguously?

The individual measurement processes of the two observers should be spacelike separated.

The individual measurement processes of the two observers should be spacelike separated.

This paper [16] defines an individual measurement to last from the first point in time, which can influence the choice of the analyzer setting until the final registration of the photon, i.e. individual measurement so quick that it is impossible for any information about it to travel via any (possibly unknown) channel to the other observer before he, in turn, finishes his measurement. The selection of analyzer direction has to be completely unpredictable, which requires the need for a **physical random number generator**. A pseudo-random number generator cannot be used since its state at any time is predetermined. To achieve complete independence of both observers, one should avoid any common context, as would be conventional registration of coincidences in all previous experiments. Rather, the individual events should be registered on both sides independently and compared only after the measurements are finished. This **requires independent and highly accurate time bases on both sides.**

To achieve complete independence of both observers, one should avoid any common context, as would be conventional registration of coincidences in all previous experiments. Rather, the individual events should be registered on both sides independently and compared only after the measurements are finished.

This experiment demonstrated several ingenuities as well as technological advancements that enabled the definitive results.

For the first time, any mutual influence between the two observations was excluded from the realm of Einstein's locality. The two observers, Alice and Bob, were spatially separated by 400 m across the Innsbruck University campus. This implied that the individual measurements, as defined earlier, had to be shorter than 1.3 ms, the time for direct communications at the speed of light. The duration of an individual measurement was kept far below the 1.3 ms limit using high-speed physical random generators and fast electro-optic modulators. **Independent data registration** was performed by each observer having their **own time interval analyzer** (75 ps resolution and 0.5 ns accuracy) and **atomic clock** (rubidium standard), synchronized only once before each experiment cycle. The source of photon pairs was degenerate Type II SPDC, which provided a much higher signal compared to the calcium cascade-based ones used earlier. Silicon avalanched photodiodes (APDs) with dark count rates, DCR (noise) of a few hundred per second, small compared to the 10,000–15,000 signal counts per second per detector were used in place of the earlier lower efficiency and higher DCR PMTs.

Figure 15 shows a schematic of one of the observer stations.

The experimental runs were performed with the settings 0°, 45° for Alice's and 22.5°, 67.5° for Bob's polarization analyzer. A typical observed value of the Bell parameter S was $S = 2.73 + / - 0.02$ for 14700 coincidence events collected in 10 seconds.

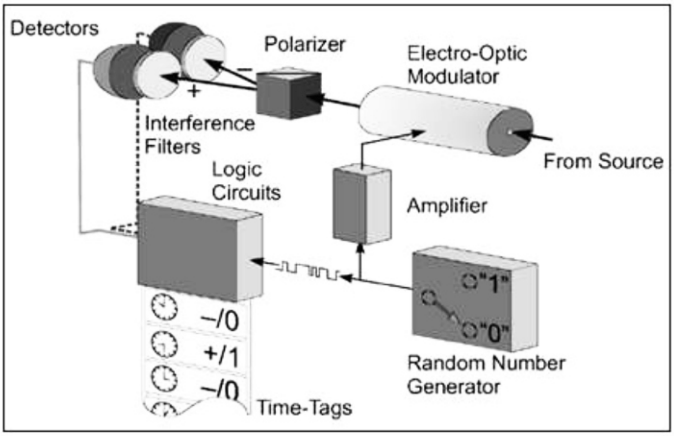


Figure 15. A schematic of one of the observer stations. The EOM (electro-optic modulator) is driven by a physical random number generator. Silicon APDs are used as single photon detectors. A time tag is stored for each detected photon together with the corresponding random number, i.e., 0 or 1 and the code for the detector, i.e., + or –, corresponding to the outputs of the polariser. Adapted with permission from G. Weihs et al., *Phys. Rev. Lett.*, Vol.81, No.23, pp.5039–5043, 1998. [16]

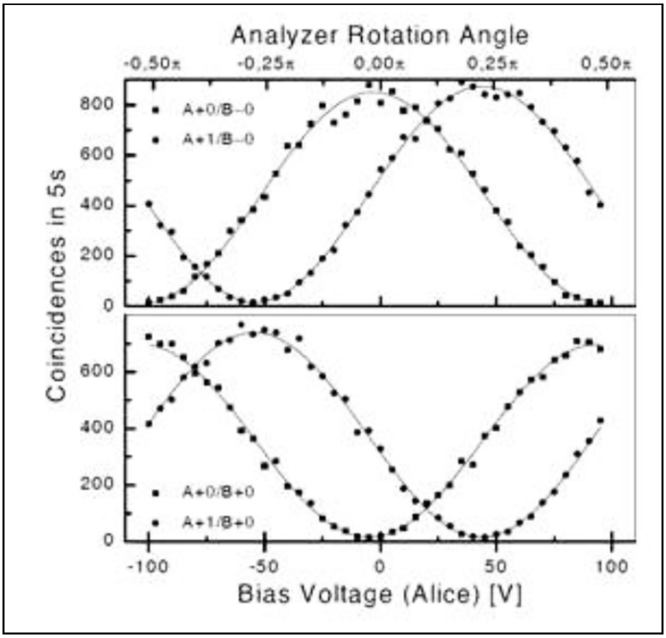


Figure 16. Four out of the sixteen coincidence rates between various detection channels as functions of bias voltage (analyzer rotation angle) on Alice's modulator. A +1/ B -0, for example, are the coincidence between Alice's '+' detector with a switch in position '1' and Bob's '-'detector with the switch in position '0'. The difference in height is explained by the different efficiencies of the detectors. Adapted with permission from G. Weihs et al., *Phys. Rev. Lett.*, Vol.81, No.23, pp.5039–5043, 1998. [16]

This corresponded to a violation of the CHSH inequality of 30 standard deviations assuming only statistical errors.

Figure 16 shows the experimental results.

So, which other major loophole remains to be closed? The experiment [16] decisively closes the locality/freedom of choice loophole. The major one that remains is the detection efficiency loophole. The **second Zeilinger experiment** [17] achieves the dream experiment: a loophole-free violation of Bell inequalities. This experiment closes all major loopholes simultaneously for the first time, including the freedom of choice loophole and the detection efficiency loophole.

As we have now gone through detailed descriptions of several experiments, we are not discussing all the intricacies of this experiment in detail. However, it is noteworthy that they use two ingenious schemes to close the detection efficiency loophole. One is the use of high-efficiency superconducting detectors (with efficiency greater than what would be the critical detection efficiency, for instance, for a CHSH Bell inequality experiment), and the other is using a completely different form of the Bell inequality altogether. Instead of the CHSH form of the Bell inequality, they use the Eberhard inequalities [18].

This brings us to a very important question: Why is a loophole free violation of Bell inequalities such a big deal?

Why is a loophole free violation of Bell inequalities such a big deal?

Figure 17 below shows the timeline for the Bell inequality experiments. As we can see, the first EPR paradox paper appeared in 1935. John Bell's thought experiment on Bell inequalities was devised in 1964. Then came the series of Bell inequality violation experiments, the seminal ones have been discussed in this article. Each experiment improved upon the previous one and brought about scientific and technological advancements that helped make the experiments more and more free from ambiguities/loopholes. It was only in ~2015 that the first loophole-free Bell inequality experiment was performed by Anton Zeilinger and his colleagues, along with two more loophole-free experiments in the same year [19, 20]. Thus, it took several decades to reach this feat. Why did the scientific community spend so much time, energy and resources towards this ultimate goal? The aim has been summarized beautifully in [21]. While, indeed, the loophole experiment removes all doubts that quantum mechanics is real and complete, it does something way more important as well. It actually leads to new capabilities in quantum information and security. A loophole-free test demonstrates not only that particles can actually be entangled but also that the source of entangled particles is working as it was intended to and has not been tampered with. The applications that follow include perfectly secure quantum key distribution (QKD) as well as unhackable sources of truly random numbers (an absolute requirement in many applications, including secure communications.

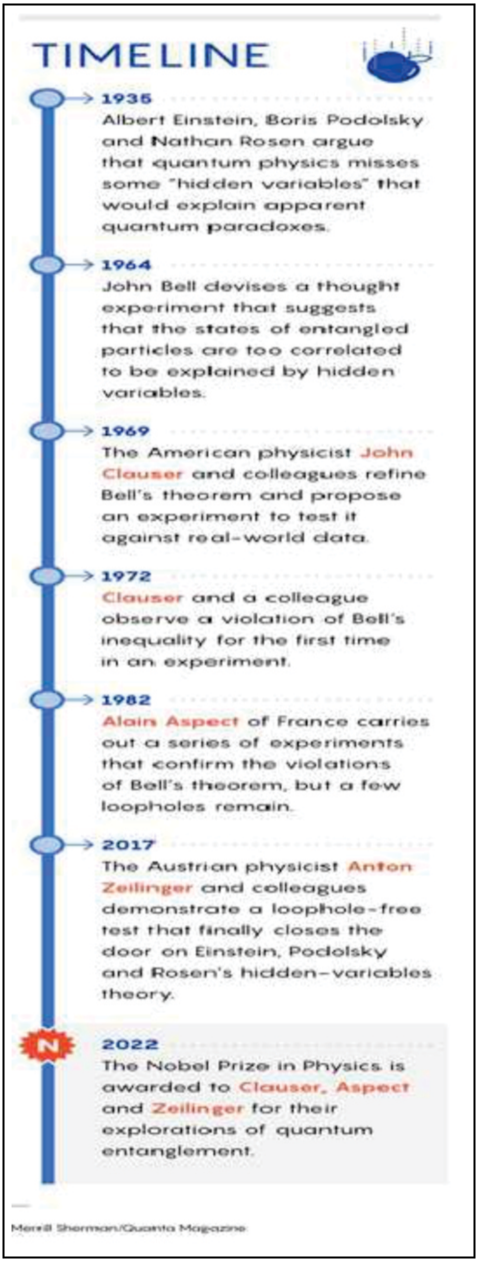
While, indeed, the loophole experiment removes all doubts that quantum mechanics is real and complete, it does something way more important as well. It actually leads to new capabilities in quantum information and security.

The technical write-up on this year's Nobel Prize in Physics by the Royal Swedish Academy of Sciences beautifully demonstrates this point. While a part of the Nobel Prize has been awarded to experiments in entanglement and violations of Bell inequalities, another major citation is the pioneering of the entire field of quantum information science itself. Quoting from the write-up (`https://www.nobelprize.org/uploads/2022/10/advancedphysicsprize2022-2.pdf`), "the main importance of the results is not to once again confirm that quantum mechanics is correct, but rather to enable even more secure QKD protocols. Since these depend on Bell tests, the issue here is not whether Nature conspires to violate Bell inequalities, but whether the evil eavesdropper Eve does. In 2022, three groups used loophole-free Bell tests to experimentally realize device-independent QKD protocols [22–24]. This means that the key is secure, even if Eve has access to the quantum hardware that runs the distribution."

While a part of the Nobel Prize 2022 has been awarded to experiments in entanglement and violations of Bell inequalities, another major citation is the pioneering of the entire field of quantum information science itself.

Anton Zeilinger's Nobel Prize is not just for his contributions to the violation of Bell inequalities. He is also the first person to perform **the first experiment on quantum teleportation** [25] along with his group. Moreover, his group also performed **the first experiment on entanglement swapping** [26]. Both of these experiments have also contributed to his share of the Nobel Prize.

The violation of Bell inequalities, as well as entanglement itself, are the main workhorses for several modern advances in quantum communications, making it one of the most happening fields of research today and for the foreseeable future. Thus, the prize this year is not for contributions that belong to the class of "old hat". In fact, the technologies that our Nobel laureates have devised so ingeniously for closing the loopholes are used in modern



TIMELINE

1935
Albert Einstein, Boris Podolsky and Nathan Rosen argue that quantum physics misses some "hidden variables" that would explain apparent quantum paradoxes.

1964
John Bell devises a thought experiment that suggests that the states of entangled particles are too correlated to be explained by hidden variables.

1969
The American physicist John Clauser and colleagues refine Bell's theorem and propose an experiment to test it against real-world data.

1972
Clauser and a colleague observe a violation of Bell's inequality for the first time in an experiment.

1982
Alain Aspect of France carries out a series of experiments that confirm the violations of Bell's theorem, but a few loopholes remain.

2017
The Austrian physicist Anton Zeilinger and colleagues demonstrate a loophole-free test that finally closes the door on Einstein, Podolsky and Rosen's hidden-variables theory.

2022
The Nobel Prize in Physics is awarded to Clauser, Aspect and Zeilinger for their explorations of quantum entanglement.

Merrill Sherman/Quanta Magazine

Figure 17. The timeline for the Bell inequality experiments. (Source: *Quanta Magazine*, October 2022 edition.)

times towards significant advancements. For instance, the EOM-based fast switching finds applications in several QKD experiments [27–31]. Similarly, the use of the physical random number generator in Zeilinger's experiment on closing the freedom of choice loophole was, in fact, recently used by my own group to come up with globally competitive key rates and quantum bit error rates (QBER) [32] for a modified version of a B92 experiment [33].

What these prizewinning experiments will help enable would be a global secure quantum communications network [34]. This will have quantum repeaters with quantum relays and quantum memories involving quantum teleportation and entanglement swapping (recall that the first experiments in both teleportation and swapping are a part of the Nobel Prize). Breakthrough results in these domains are happening as we speak, for instance, in quantum teleportation [35–37] and entanglement swapping [38], quantum memories and repeaters [39–41]. Another revolutionary area is that of device-independent random number generation, which has already seen very exciting results [42–44]. In order to increase the distance of quantum communications to a global scale, an approach that is being increasingly explored by all nations that wish to be in the quantum race is that of satellite-based quantum communications. The Micius satellite has already demonstrated the feasibility of the idea through several demonstrations [45–47], but there is a lot left to do. My own lab is working on India’s first project on satellite-based quantum communications called Quantum Experiments with Satellite Technology, in collaboration with ISRO. We have achieved several national firsts, including the first free space QKD experiment that has been published in an internationally peer-reviewed journal [32], the first demonstration of QKD between two buildings using an atmospheric free space channel using entanglement as a resource (`https://www.rri.res.in/quic/index.php`), as well as many other ground-based milestones. We are now working on the space segment, and we hope to achieve satellite-based QKD between two Indian ground stations using an Indian satellite as a trusted node in the foreseeable future.

In order to increase the distance of quantum communications to a global scale, an approach that is being increasingly explored by all nations that wish to be in the quantum race is that of satellite-based quantum communications.

As Isaac Asimov is quoted to have said “Today’s Science is Tomorrow’s Technology”. The Nobel Prize in Physics 2022 is indeed a fitting example of this thought. It has been awarded for experiments that have revolutionised fundamental science as well as led to disruptive technologies that are the most exciting technologies of today and tomorrow.

Acknowledgements

The author wishes to thank Aninda Sinha for proof reading the article and Saumya Ranjan Behera for his assistance.

Suggested Reading

[1] **Nielsen, Michael A and Chuang, Isaac, Quantum computation and quantum information, s.l.: *American Association of Physics Teachers*, 2002.**

[2] **Die gegenwärtige Situation in der Quantenmechanik. Schrödinger, E. 50, s.l.: *Naturwissenschaften*, Vol.23, pp.844–849. 1935.**

[3] **Minkowski, Hermann, Raum und Zeit. s.l.: Physikalische Zeitschrift, 1909.**

[4] **Bell's theorem: does quantum mechanics contradict relativity? Ballentine, Leslie E and Jarrett, Jon P. 8, s.l.: American Association of Physics Teachers, *American Journal of Physics*, Vol.55, pp. 697–701, 1987.**

[5] **Can Quantum-Mechanical Description of Physical Reality Be Considered Complete? Einstein, A. and Podolsky, B. and Rosen, N.10, *Phys. Rev.*, Vol.47, pp.777–780.**

[6] **Realism and the physical world, Leggett, A J. 2, *Reports on Progress in Physics*, Vol.71, p.022001, 2008.**

[7] **Einstein and the quantum theory, Pais, A. 4, *Rev. Mod. Phys.*, Vol.51, pp.863–914, 1979.**

[8] **On the Einstein Podolsky Rosen paradox, Bell, J. S. 3, *Physics Physique Fizika*, Vol.1, pp.195–200, 1964.**

[9] **Proposed Experiment to Test Local Hidden-Variable Theories, Clauser, John F. and Horne, Michael A. and Shimony, Abner and Holt, Richard A. 16, *Phys. Rev. Lett.*, Vol.23, pp.880–884, 1969.**

[10] **Quantum analogues of the Bell inequalities, The case of two spatially separated domains, Tsirel'son, B. S. 4, *Journal of Soviet Mathematics*, Vol.36, pp.557–570, 1987.**

[11] **Experimental Test of Local Hidden-Variable Theories. Freedman, Stuart J. and Clauser, John F. 14, *Phys. Rev. Lett.*, Vol.28, pp.938–941, 1972.**

[12] **Experimental Tests of Realistic Local Theories via Bell's Theorem. Aspect, Alain and Grangier, Philippe and Roger, Gérard, 7, *Phys. Rev. Lett.*, Vol.47, pp.460–463, 1981.**

[13] **Experimental Realization of Einstein-Podolsky-Rosen-Bohm Gedankenexperiment: A New Violation of Bell's Inequalities, Aspect, Alain and Grangier, Philippe and Roger, Gérard, 2, *Phys. Rev. Lett.*, Vol.49, pp.91–94, 1982.**

[14] Experimental Test of Bell's Inequalities Using Time-Varying Analyzers. Aspect, Alain and Dalibard, Jean and Roger, Gérard, 25, *Phys. Rev. Lett.*, Vol.49, pp.1804–1807, 1982.

[15] Proposed experiment to test the nonseparability of quantum mechanics. Aspect, Alain, 8, *Phys. Rev. D*, Vol.14, pp.1944–1951, 1976.

[16] Violation of Bell's Inequality under Strict Einstein Locality Conditions. Weihs, Gregor and Jennewein, Thomas and Simon, Christoph and Weinfurter, Harald and Zeilinger, Anton, 23, *Phys. Rev. Lett.*, Vol.81, pp.5039–5043, 1998.

[17] Significant-Loophole-Free Test of Bell's Theorem with Entangled Photons, Giustina, Marissa and Versteegh, Marijn A. M. and Wengerowsky, Sören and Handsteiner, Johannes and Hochrainer, Armin and Phelan, Kevin and Steinlechner, Fabian and Kofler, Johannes and Larsson, Jan-Åke and Abellán, Carlos and Amaya, Waldimar and P. 25, *Phys. Rev. Lett.*, Vol.115, p.250401, 2015.

[18] Background level and counter efficiencies required for a loophole-free Einstein-Podolsky-Rosen experiment. Eberhard, Philippe H. 2, *Physical Review A*, Vol.47, p.R747, 1993.

[19] Loophole-free Bell inequality violation using electron spins separated by 1.3 kilometres, Hensen, B. 7575, *Nature*, Vol.526, pp.682–686, 2015.

[20] Strong Loophole-Free Test of Local Realism. Shalm, Lynden K. and Meyer-Scott, Evan and Christensen, Bradley G. and Bierhorst, Peter and Wayne, Michael A. and Stevens, Martin J. and Gerrits, Thomas and Glancy, Scott and Hamel, Deny R. and Allman, Michael S. and Coakley, Kevin J. and Dyer, Shellee D. 25, *Phys. Rev. Lett.*, Vol.115, p.250402, 2015.

[21] Miller, Johanna L, Three groups close the loopholes in tests of Bell's theorem. s.l. *Physics Today* 69, pp.14–16, 2016.

[22] Experimental quantum key distribution certified by Bell's theorem, Nadlinger, D. P. 7920, *Nature*, Vol.607, pp.682–686, 2022.

[23] A device-independent quantum key distribution system for distant users, Zhang, Wei, 7920, *Nature*, Vol.607, pp.687–691, 2022.

[24] Toward a Photonic Demonstration of Device-Independent Quantum Key Distribution. Liu, Wen-Zhao and Zhang, Yu-Zhe and Zhen, Yi-Zheng and Li, Ming-Han and Liu, Yang and Fan, Jingyun and Xu, Feihu and Zhang, Qiang and Pan, Jian-Wei. 5, *Phys. Rev. Lett.*, Vol.129, p.050502, 2022.

[25] Experimental quantum teleportation. Dik Bouwmeester, Jian-Wei Pan, Klaus Mattle, Manfred Eibl, Harald Weinfurter & Anton Zeilinger, *Nature*, Vol.390, pp.575–579, 1997.

[26] Experimental Entanglement Swapping: Entangling Photons That Never Interacted. Pan, Jian-Wei and Bouwmeester, Dik and Weinfurter, Harald and Zeilinger, Anton, 18, *Phys. Rev. Lett.*, Vol.80, pp.3891–3894, 1998.

[27] Chip-based quantum key distribution, Sibson, P.1, *Nature Communications*, Vol.8, p.13984, 2017.

[28] Intrinsically Stable 2-GHz Polarization Modulation for Satellite-Based Quantum Key Distribution. Luo, Wenbin and Li, Yang and Li, Yuhuai and Tao, Xueying and Han, Liying and Cai, Wenqi and Yin, Juan and Ren, Jigang and Liao, Shengkai and Peng, Chengzhi. 5, *IEEE Photonics Journal*, Vol.14, pp.1-6, 2022.

[29] Fast polarization QKD scheme based on LiNbO3 phase modulators, Duplinskiy, A and Ustimchik, V and Kanapin, A and Kurochkin, Y., *International Conference on Micro-and Nano-Electronics*, Vol.10224, pp.762–768, 2016.

[30] Experimental quantum key distribution with source flaws. Xu, Feihu and Wei, Kejin and Sajeed, Shihan and Kaiser, Sarah and Sun, Shihai and Tang, Zhiyuan and Qian, Li and Makarov, Vadim and Lo, Hoi-Kwong, 3, *Phys. Rev. A*, Vol.92, p.032305, 2015.

[31] Tunable electro-optic polarization modulator for quantum key distribution applications. Buller, Nikita Yu. Gordeev and Karen J. Gordon and Gerald S., 1, *Optics Communications*, Vol.234, pp.203–210, 2004.

[32] qkdSim, a Simulation Toolkit for Quantum Key Distribution Including Imperfections: Performance Analysis and Demonstration of the B92 Protocol Using Heralded Photons. Chatterjee, Rishab and Joarder, Kaushik and Chatterjee, Sourav and Sanders, Barry C. and Sinha, Urbasi, 2, *Phys. Rev. Appl.*, Vol.14, p.024036, 2020.

[33] Experimental quantum cryptography, Bennett, Charles H. 1, *Journal of Cryptology*, Vol.5, pp.3–28, 1992.

[34] Quantum secure direct communication and deterministic secure quantum communication, Long, Gui-lu. 3, Frontiers of Physics in China, Vol.2, pp.251–272, 2007.

[35] Experimental free-space quantum teleportation, Jin, Xian-Min, 6, *Nature Photonics*, Vol.4, pp.376–381, 2010.

[36] Quantum teleportation over 143 kilometres using active feed-forward, Ma, Xiao-Song, 7415, *Nature*, Vol.489, pp.269–273, 2012.

[37] Ground-to-satellite quantum teleportation. Ren, Ji-Gang, 7670, *Nature*, Vol.549, pp.70–73, 2017.

[38] All-Optical Entanglement Swapping. Liu, Shengshuai and Lou, Yanbo and Chen, Yingxuan and Jing, Jietai, 6, *Phys. Rev. Lett.*, Vol.128, p.060503, 2022.

[39] Entangling single atoms over 33km telecom fibre, van Leent, Tim, 7917, *Nature*, Vol.607, pp.69–73, 2022.

[40] Postselected Entanglement between Two Atomic Ensembles Separated by 12.5 km. Luo, Xi-Yu and Yu, Yong and Liu, Jian-Long and Zheng, Ming-Yang and Wang, Chao-Yang and Wang, Bin and Li, Jun and Jiang, Xiao and Xie, Xiu-Ping and Zhang, Qiang and Bao, Xiao-Hui and Pan, Jian-Wei, 5, *Phys. Rev. Lett.*, Vol.129, p.050503, 2022.

[41] Entanglement of two quantum memories via fibres over dozens of kilometres, Yu, Yong. 7794, *Nature*, Vol.578, pp.240–245, 2020.

[42] Device-independent randomness expansion with entangled photons, Shalm, Lynden K. 4, *Nature*, Vol.17, pp.452–456, 2021.

[43] Experimentally generated randomness certified by the impossibility of superluminal signals, Bierhorst, Peter, 7700, *Nature*, Vol.556, pp.223–226, 2018.

[44] Random numbers certified by Bell's theorem. Pironio, S, 7291, 2010, *Nature*, Vol.464, pp.1021–1024, 2018.

[45] An integrated space-to-ground quantum communication network over 4,600 kilometres, Chen, Yu-Ao. 7841, *Nature*, Vol.589, pp.214–219, 2021.

[46] Entanglement-based secure quantum cryptography over 1,120 kilometres, Yin, Juan, 7813, *Nature*, Vol.582, pp.501–505, 2020.

[47] Satellite-to-ground quantum key distribution, Liao, Sheng-Kai, 7670, Nature, Vol. 549, pp.43–47, 2017.

Address for Correspondence
Urbasi Sinha
Quantum Information and
Computing Lab
Light and Matter Physics group
Raman Research Institute
C. V. Raman Avenue,
Sadashivanagar
Bengaluru 560 080, India
Email: `usinha@rri.res.in`