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Brief Considerations on the 2022 Nobel Prize in Physics

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ABSTRACT

The Nobel Prize in Physics in 2022 was awarded in equal parts to Alain Aspect of the University of Paris-Saclay, John F. Clauser of J. F. Clauser & Associates, and Anton Zeilinger of the University of Vienna, for their remarkable work in quantum mechanics and quantum information science. Working independently, each of the three researchers forged new experiments demonstrating and investigating quantum entanglement, the curious phenomenon in which two or more particles exist in a so-called entangled state. In this bizarre situation, an action taken on one of the particles can instantaneously ripple through the entire entangled assemblage, predicting the other particles' behavior, even if they are far apart. This phenomenon has become an essential aspect of modern quantum Technologies. One possibility mooted by physicists was that the particles might contain some secret information or "hidden variables", that determine their properties.

Keywords: Aspect, Clauser, Zeilinger, entangled photons.

INTRODUCTION

The 2022 Nobel Prize in Physics (1) went to three laureates: Alain Aspect, John F. Clauser and Anton Zeilinger. The honor was made due to his research in quantum physics. The studies developed by the three researchers involved experiments with entangled photons. The result enables new paths for technologies that are based on quantum physics and also opens up new theoretical possibilities about the field of study. Quantum physics is the area dedicated to the study of tiny particles that make up the universe and the interactions that occur between them. An important concept for this scientific field is the entangled state. The idea is that, when something happens to a particle, the phenomenon will also happen to other particles that are in this entangled pair, even if they are very far from each other. A comparison would be to a machine that throws white and black balls in opposite directions. A person on one side receives a white ball and then concludes that the ball on the opposite side was black. When this situation is analyzed from the perspective of quantum physics, the explanation becomes somewhat more complex. The balls would be the particles and they would be in an entangled pair because, when someone receives one of them, he can already determine the state and color of the other. However, for quantum physics, the property of these balls before being launched would actually be gray. It is only when one of the people notices that the received ball is black that the color of the other person changes, becoming white. Aspect, Clauser and Zeilinger's research is part of this complex field of investigation into the entangled state of particles. They are complementary and call into question the concept of mathematical inequality, proposed by physicist John Stewart Bell. In addition to the new discoveries, the research of the three were recognized by the Nobel Prize because of the ability they have to generate practical applications of quantum physics. Alain Aspect, John Clauser and Anton Zeilinger conducted innovative experiments using entangled quantum states, where two particles behave as a single unit, even when they are separate. Their results paved the way for new technologies based on quantum information. A key factor in this development is how quantum mechanics allows two or more particles to exist in what is called an entangled state. What happens to one of the particles in an entangled pair determines what happens to the other particle, even if they are far apart.

BRIEF BIOGRAPHY OF THE NOBELISTS

DAVOUR (1) presents an excellent biography referring to the three Nobel Prize winners of 2022. Alain Aspect, born on June 15, 1947 in Agen, is a French physicist and academic known for having conducted the first conclusive test on one of the fundamental paradoxes of quantum mechanics, the Einstein-Podolsky-Rosen paradox. His primary education was spent at school in Astaffort. A former student of the École normale supérieure de Cachan, Alain Aspect continued his studies at the University of Paris. He obtained a BA in physics in 1967, then the diploma of advanced studies in optics in 1968. Recruited as an associate professor of physical sciences in 1969, he was posted as an assistant at the University of Paris-Sud from 1969 to 1971. In 1971 he left to teach, as part of the cooperation, at the École normale supérieure in Yaoundé (Cameroon) until 1974. In 1975 and 1976 he published two articles in which he proposed the experiments that he would carry out a few years later. He earned a doctorate in State in 1983, settling an old debate between Albert Einstein and Niels Bohr over the foundations of quantum mechanics, and leading to the obligation to choose between the principles of causality and locality. In 1984, he was appointed professor at the École Polytechnique and deputy laboratory director at the Collège de France. In 1992 he returned to Orsay at the Institut d'Optique as director of research at the CNRS. He was deputy director of SupOptique from 1992 to 1994. There he created a new research group dedicated to atomic optics, atomic mirrors and Bose-Einstein condensates. He is also a co-founder in 2019 from the start-up Pasqual, a company specializing in quantum computing, which is working on a quantum computer with neutral atoms. As of 2021, he is a visiting professor at the Conservatoire National des Arts et métiers.

John F. Clauser (1) was born in Pasadena, California. He received a bachelor's degree in physics from the California Institute of Technology in 1964. He received a master's degree in physics in 1966 and a doctorate of philosophy in physics in 1969 from Columbia University [1] under the direction of Patrick Thaddeus. From 1969 to 1996, he worked primarily at the Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory, and the University of California at Berkeley. In 1972, working with Stuart Freedman, he performed the first experimental test of the predictions of the CHSH-Bell theorem. This was the first experimental observation of a violation of a Bell inequality. In 1974, working with Michael Horne, he showed for the first time that a generalization of Bell's Theorem provides severe restrictions for all realistic local theories of nature (also known as objective local theories). This work introduced the Clauser-Horne inequality (CH) as the first fully general experimental requirement established by local realism. He also introduced the "no-increasing CH assumption", where the CH inequality reduces to the CHSH inequality, and where the associated experimental tests also constrain local realism. Also in 1974 he made the first observation of sub-Poissonian statistics for light (through a violation of the Cauchy-Schwarz inequality for classical electromagnetic fields), and thus for the first time demonstrated univocal particle character for photons. . In 1976 he performed the world's second experimental test of the predictions of the CHSH-Bell theorem. Clauser received the Wolf Prize in Physics in 2010, along with Alain Aspect and Anton Zeilinger. The three also jointly received the Nobel Prize in Physics in 2022.

Anton Zeilinger (1) was born in 1945 in Ried in Innkreis, Upper Austria. He studied physics and mathematics at the University of Vienna from 1963 to 1971. He received a PhD from the University of Vienna in 1971 with a thesis on "Measurements of Neutron Depolarization in a Dy-single Crystal" under the supervision of Helmut Rauch. He qualified as a university professor (habilitation) at the Technical University of Vienna in 1979. Zeilinger has held positions at TU Wien and the University of Innsbruck. He has held visiting positions at the Massachusetts Institute of Technology, Humboldt University in Berlin, Merton College, Oxford and the Collège de France in Paris. Anton Zeilinger is currently Professor Emeritus of Physics at the University of Vienna and Senior Scientist at the Institute of Quantum Optics and Quantum Information of the Austrian Academy of Sciences. He was president of the Austrian Academy of Sciences from 2013 until 2022. Since 2006, Zeilinger has been the vice-chairman of the board of directors of the Austrian Institute of Science and Technology, an ambitious project initiated by Zeilinger's proposal. In 2009, he founded the Traunkirchen International Academy, which is dedicated to supporting talented students in science and technology. Zeilinger received the Wolf Prize in Physics in 2010 along with Alain Aspect and John Clauser. The three were also joint recipients of the 2022 Nobel Prize in Physics. Zeilinger also received the inaugural Isaac Newton Medal from the Institute of Physics in 2007 and the King Faisal International Prize in 2005.

WHAT IS QUANTIC ENTANGLEMENT?

According to SUTTER (2) the strange part of quantum entanglement is that when you measure it, weird behaviors are observed. In a very common demonstration, the quantum particles used as qubits in a quantum computer are 0 and 1 at the same time until observed, at which point they randomly appear to become 0 or 1. Now, in simple terms, quantum entanglement is when two particles are produced or interact in such a way that the main properties of these particles cannot be described independently of one another. For example, if two photons are generated and entangled, one particle may have a clockwise spin on one axis, so the other will necessarily have a counterclockwise spin on that same axis. By itself, this is not so radical. But since particles in quantum mechanics can also be described as wave functions, the act of measuring a particle's spin is said to "collapse" its wave function to produce this measurable property (like going from 0 and 1 to just 0 or just 1). When you do that with entangled particles, however, we get to the really amazing part of quantum entanglement. When you measure an entangled particle to determine its spin along some axis and collapse its wave function, the other particle also collapses to produce the measurable property of spin, even though you haven't observed the other particle. If a pair of entangled particles is a 0 and a 1, and you measure one particle as a 0, the other entangled particle will automatically collapse to produce a 1, entirely on its own and without any interaction from the observer. This seems to happen instantly and regardless of the distance between them. This fact originally led to the paradoxical conclusion that information about the measured particle's spin is somehow being transmitted to its entangled partner. It happens faster than the speed of light. SOUZA (3), says that quantum entanglement, or at least the principles that describe the phenomenon, was first proposed by Einstein and his colleagues Boris Podolsk and Nathan Rosen. All this is described in a 1935 article in the journal (4) Physical Review entitled Can Quantum-Mechanical Description of Physical Reality Be Considered Complete. In it, Einstein, Podolsky and Rosen argued that an especially strong correlation of quantum states between particles can lead them to have a single unified quantum state. The first use of the word “entanglement” to describe this phenomenon belongs to Erwin Schrödinger (5), who recognized it as one of the most fundamental features of quantum mechanics and argued that it was not a mystery that would soon be solved under relativity, but rather a strong break with classical physics entirely. They also determined that this unified state can result in the measurement of one strongly correlated particle having a direct effect on another strongly correlated particle without considering the distance between the two particles. Bohm and Ahronov face EPR. For LUCHT (6,7), the Ahronov-Bohm effect, in 1957, reformulated Podolsky's version of the EPR paradox that was based on continuous values of position and momentum and replaced it with a much simpler model based on the Stern-Gerlach effect in spins and beyond the case of positronium decay into two photons with correlated polarizations. D’ESPAGNAT (8) was a French theoretical physicist, philosopher of science, and author, best known for his work on the nature of reality. D'Espagnat's work on Bell's theorem led him to reject conventional realism, but the fact that scientific theories remain falsifiable by experiment suggests that a veiled reality underlies the phenomena of physics. There is a theorem called Bell's theorem, in which it was proved that all bodies are connected, everything in the universe is connected. It's one of the biggest dilemmas in modern physics. From it comes various types of theories, such as string theory

IS QUANTUM ENTANGLEMENT REAL?

Quantum entanglement (3,4) is not only real, but it is also an important component of emerging technologies such as quantum computing and quantum communications. In quantum computing, how can you operate on qubits in a quantum processor. The quantum computer works from what we call a qubit, which is a particle at the subatomic level. The qubit supports two states at the same time, which doubles its processing capacity. How do you detect errors without looking at the qubits and destroying the whole engine that makes quantum computing so powerful? Quantum entanglement of several particles in a row is vital for putting enough distance between the qubits and the outside world to keep the vital qubits in superposition long enough for them to perform calculations. Quantum communications is another area of research that hopes to take advantage of quantum entanglement to facilitate communication, although that doesn't mean faster-than-light communication is on the horizon (in fact, such a technology is probably impossible). When discussing quantum entanglement, one usually uses an example of two entangled particles behaving in a certain way to demonstrate the phenomenon, but this is an oversimplification of an incredibly complex quantum system. However, the reality is that a given particle can be entangled with many different particles to varying degrees, not just in the “maximum entangled” state, where two particles are correlated with one and only with the other. This is why measuring one part of an entangled pair does not automatically guarantee that you will know the state of the other particle in real-world applications, as that other particle has other entanglements that it is also maintaining. This gives you a better than random chance of knowing the state of the other particle.

WHY IS QUANTUM ENTANGLEMENT IMPORTANT?

According to FARIAS (9), quantum entanglement is important for two main reasons. First, quantum entanglement is such a fundamental mechanism of the quantum world, at the same time we can directly interact with and influence it. It could provide a fundamental way to harness some of the universe's most fundamental properties to advance our technology to new heights. We know how to entangle particles, and we do it regularly both in labs and in real-world applications like quantum computers. Quantum computers, in particular, demonstrate the potential of quantum mechanics in modern technology, and quantum entanglement is the best tool we have to really leverage quantum mechanics in this way. The other big reason quantum entanglement matters is that it's a signal that points to something truly fundamental about our universe. It's about as clear a demonstration as you can get that the quantum world is almost a purer form of the universe than we can see and that it obeys laws that we can explain. Perhaps the most widely used application of quantum entanglement is in cryptography. According to Caltech Magazine (9), in this scenario, a sender and a receiver build a secure communication link that includes pairs of entangled particles. The sender and receiver use the entangled particles to generate private keys, known only to them, which they can use to encrypt their messages. If someone intercepts the signal and tries to read the private keys, the entanglement breaks down, because measuring an entangled particle changes its state. This means that both the sender and receiver will know that their communications have been compromised. Another application of entanglement is quantum computing, in which large numbers of particles are entangled, thus allowing them to work together to solve some large and complex problems.

QUANTUM TELETRANSPORTATION

MALEWAR (10), says it's important not to confuse this application with science fiction teleportation. Quantum teleportation is sending information over long distances, not sending matter anywhere. It is possible that this kind of "teleportation" (of information) will lay the groundwork for a new internet. Contrary to the usual use of the word "teleportation", quantum teleportation does not involve the movement or translation of the particles themselves. Instead, in quantum teleportation, information about a quantum state is transported across vast distances and replicated elsewhere. It's best to think of quantum teleportation as the quantum version of traditional communication. First, an emitter prepares a particle to contain the information (that is, the quantum state) it wants to transmit. Then they combine this quantum state with one of a pair of entangled particles. This causes a corresponding change in the other entangled pair, which may be sitting an arbitrary distance apart. The receiver then registers the change in the mated partner of the pair. Finally, the sender must transmit, through normal channels (that is, limited by the speed of light), the original change made to the entangled pair. This allows the receiver to rebuild the quantum state in the new location. GRANT (11) mentions that quantum teleportation is a technology that allows the teleportation of information (1), such as spin or polarization, by exclusively quantum means, which are independent of transmission means. Bandwidth for quantum teleportation doubled in 2015. It's a Chinese technique of transferring information about a particle so that another particle takes on two, rather than just one, of the original particle's quantum properties. Teleportation has been demonstrated on many experimental quantum information processing platforms, teleportation using electromagnetic photons to create remotely entangled pairs of qubits, and is an essential tool for quantum error correction, measurement-based quantum computing, and quantum gate teleportation. The company D-Wave produces quantum computers based on spins. One of the physics and engineering techniques used is the use of graphene, since electrons move as if they had no mass. Today there are several libraries for quantum computing. Many of them use the OpenQASM language as a low-level interpreter. There are also frameworks for quantum computing, such as Qiskit, which can be used in languages such as Python 3.

QUANTIC BIT

In the 1990s, the quest for quantum clarity took a new turn with the emergence of quantum information theory (3). Physicist John Archibald Wheeler, a disciple of Bohr, had long emphasized that specific realities emerge from the fog of quantum possibilities by irreversible amplifications – like an electron definitively establishing its location by leaving a mark after hitting a detector. Wheeler suggested that reality as a whole could be constructed out of such processes, which he likened to the question: Is the electron here? Yes, or No. The answers corresponded to bits of information, the numbers 1 and 0 used by computers. Wheeler coined the slogan “it from bit” to describe the link between existence and information. He introduced the quantum bit, or qubit, at a conference in Dallas in 1992. Schumacher's qubit provided a basis for building computers capable of processing quantum information. These “quantum computers” had already been imagined, in different ways, by physicists Paul Benioff, Richard Feynman and David Deutsch. In 1994, mathematician Peter Shor showed how a quantum computer manipulating qubits could crack the most difficult secret codes, launching a quest to design and build quantum computers capable of this and other intelligent computing feats. In the early 21st century, rudimentary quantum computers were built; newer versions can perform some computing tasks, but are still not powerful enough to make current encryption methods obsolete. For certain types of problems, however, quantum computing may soon achieve superiority over standard computers. An excellent discussion of qubits can be found in HUGHES et al (12).

TIMELINE FOR ENTANGLEMENT (13)

1935 – Einstein EPR

1935 – Bohr EPR

1935 – Schrödinger: Entanglement and Cat

1950 – Madam Wu positron decay

1952 – David Bohm and Non-local hidden variables

1957 – Bohm and Ahronov version of EPR

1963 – Bell’s inequalities

1967 – Clauser reads Bell’s paper

1967 – Commins experiment with Calcium

1969 – CHSH inequality: measurable with detection inefficiencies

1972 – Clauser and Freedman experiment

1975 – Aspect reads Bell’s paper

1976 – Zeilinger reads Bell’s paper

1981 – Aspect two-photon generation source

1982 – Aspect time variable analyzers

1988 – Parametric down-conversion of EPR pairs (Shih and Alley, Ou and Mandel)

1989 – GHZ state proposed

1993 – Bennett quantum teleportation proposal

1995 – High-intensity down-conversion source of EPR pairs (Kwiat and Zeilinger)

1997 – Zeilinger quantum teleportation experiment

1999 – Observation of the GHZ state

2007 to 2010 - Alain Aspect, Anton Zeilinger and John Clauser present breakthroughs in resolving the nonlocality aspect of quantum theory

2009 - Aaron D. O'Connell invents the first quantum machine.

2014 - Scientists transfer data by quantum teleportation

2019 - Quantum entanglement captured for the first time

2020 - Scientists do quantum entanglement with trillions of atoms

2021 - Quantum entanglement is directly observed on the macroscopic scale

2022 - Quantum entanglement, awarded the Nobel Prize in Physics

FINAL CONSIDERATIONS

The historical context of quantum entanglement involves the theoretical reflections proposed by Einstein, Podolsky and Rosen (3) and Schrödinger (4), as well as its recognition as a consolidated field of research in Physics (BELL (3)). This is part of a complex chain full of subtleties, producing intense debates until the present day. Such aspects make it possible to understand the development of theory and its technological applications, but, above all, of a science under construction. In agreement with these aspects, the content of the selected QM involves theory developments from 1935 with the argument of Einstein, Podolsky and Rosen (3) (EPR) about the possible incompleteness of the theory. The criticisms of these authors provoked conceptual discussions about the nature of the so-called entangled states and later motivated investments in experimental activities, highlighting the concept of non-locality. Among the relevance of this theme, for example, is that the entanglement between quantum systems phenomenon derived from the studies in question has promised applications such as quantum cryptography and quantum computers. A famous paradox, Schrödinger's cat (4), in which the coupling of a quantum system to a classical one (a cat) would lead the latter to the superposition of the states of alive/dead, simultaneously; to an absurd result, considering Classical Mechanics. About three decades later, several works were developed over that time, but for didactic purposes we opted for such a historical perspective. Bell (14) proposes a theorem that highlights non-locality and establishes the so-called Bell inequalities. A simple criterion for testing any local theory of natural phenomena is then formulated under the framework of realism and evidence that QM is not one of them. The results favorable to the QM are experimentally confirmed by the Nobelist Aspect in 1982. Entanglement (15) is then established as an effective property of the quantum world. The discussion of the EPR argument is marked by descriptions, theoretical propositions and experimental realizations that provide evidence of the paths followed for the construction of the concepts in question. The theories of hidden variables (15) are proposals that introduce additional parameters to Quantum Theory, parameters that are not directly observable, but whose values uniquely determine the result of a measurement and, on average, provide the expected values of Quantum Mechanics. In 1932, Von Neumann (5) presented his famous proof of the impossibility of hidden variables, a proof that did not encompass all possibilities of theories of hidden variables, as shown by J.S. Bell (5) only in 1966. Von Neumann's proof did not consider, among other things, the possibility that hidden variables belong to the measuring device. On the other hand, the idea of developing computers (16) whose dynamics obey the laws of Quantum Mechanics assumes, nowadays, remarkable technological and scientific importance, since the use of quantum algorithms has spread in the implementation of encryption systems and, moreover, reports of communication experiments on quantum channels are increasingly present in the literature. There are even conjectures about quantum behavior in synapses and other natural phenomena considered macroscopic. All these developments are based on the quantum theory of information (17) which, in general, can be considered as an extension of the classical theory due to Shannon, considering two peculiar aspects of quantum phenomena: the inability to obtain a copy of a quantum state and the fact that quantum states present a mutual dependence, originated in their preparation. Many large computer companies are investing billions of dollars in building quantum computers. Likewise, academic institutions also invest money and intellectual capacity in this area. The current generation of quantum computers needs to be managed by experts due to their specialized hardware and cooling requirements. As a result, for the foreseeable future, quantum computing functionality will primarily be offered as a cloud service. However, there will be customers who will want to deploy their data and host the classic compute and storage portion of their overall architecture in their own private data centers or in a co-location, primarily for privacy and control reasons, and these customers would like to take advantage of this. quantum computing functionality in a service provider. In conclusion, we are in the early stages of the era of hybrid quantum computers, where classical computers offload certain types of processing onto quantum equipment with a limited number of qubits. We believe this will be the norm for quantum computing for the next five years, before non-hybrid native quantum computers containing thousands of qubits start solving real-life problems (MATEOS (18)).

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