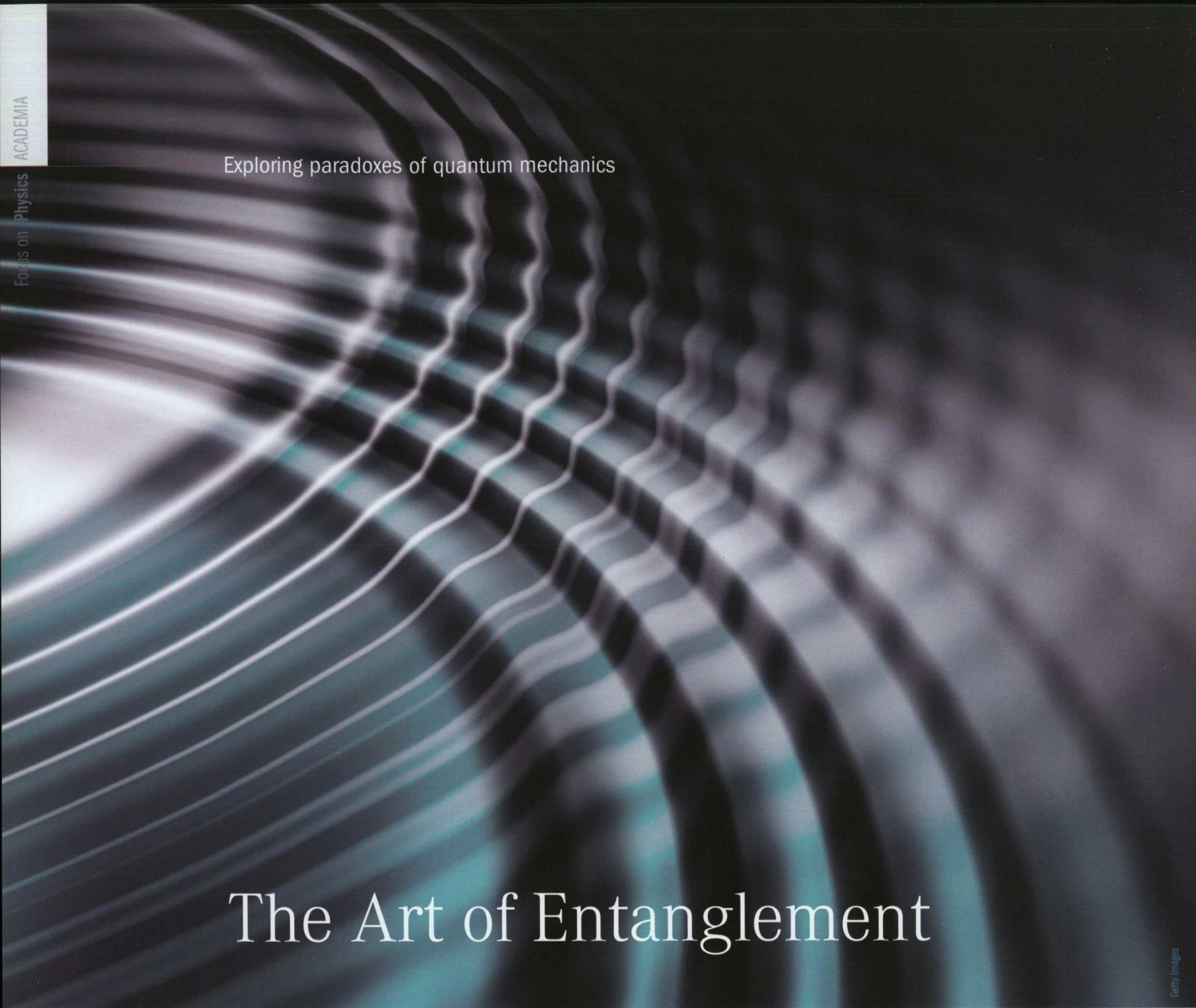
Exploring paradoxes of quantum mechanics



The Art of Entanglement

Getty Images

MAREK ŻUKOWSKI
Institute of Theoretical Physics and Astrophysics
University of Gdańsk
marek.zukowski@univie.ac.at

Prof. Marek Żukowski is the director of the Institute of Theoretical Physics and Astrophysics. In 2013, he was awarded the Prize of the Foundation for Polish Science, colloquially known as the "Polish Nobel." He was awarded the Polish Academy of Sciences Division III prize for a cycle of works, described in this article, on foundations of quantum theory and research in multiphoton quantum interferometry.

Quantum theory was discovered in 1925 independently by Werner Heisenberg and Erwin Schrödinger. The discovery was the culmination of 25 years of intensive research. Today, its interpretation remains as controversial as it is inspirational

The essence of quantum theory was expressed, basically intuitively, by Niels Bohr, who formulated the Copenhagen interpretation in 1927. It was slowly accepted by the mainstream of physicists investigating the foundations of quantum mechanics. The more pragmatic researchers adopted the attitude "Shut up and calculate!", instead of concerning themselves on the complexities of the myriad interpretations. New discoveries kept cropping up like mushrooms after the rain – quantum theory provides an excellent description of phenomena in the microworld. Yet, Albert Einstein contested Bohr's interpretation.

Quantum newspeak

The Copenhagen interpretation evolved over time, and imposed a kind of quantum newspeak. Predictions concerning quantum systems are said to depend on the wave function (alternative name: state vector), which exists only in the theory. The phrase "state of a system" is used as a shorthand for "state-of-knowledge about a quantum system". What we measure are "observables", rather than parameters of the system. The so-called wave function collapse keeps many a skeptic awake at night: following the measurement, the original wave function of the particle is suddenly replaced by a new wave function, consistent with the new, measured result. The theory gives predictions in the form of probabilities; it is fundamentally nondeterministic.

Einstein contested, "God doesn't play dice." In 1935, he used in his argumentation the phenomenon called entanglement. This is a strange trait of certain quantum states of systems comprising two (or more) separated subsystems. For example, let's take a pair of photons. Maximally entangled states define only joint properties of the pair of systems, while results of measurements on a single subsystem remain absolutely unpredictable. For example, for a so-called polarization singlet of a pair of photons, the results of a measurement of any property of polarization of one of the photons is entirely random; however, if we perform identical measurements on each of the photons, the results will always be opposite, regardless of the relative distance of the photons.

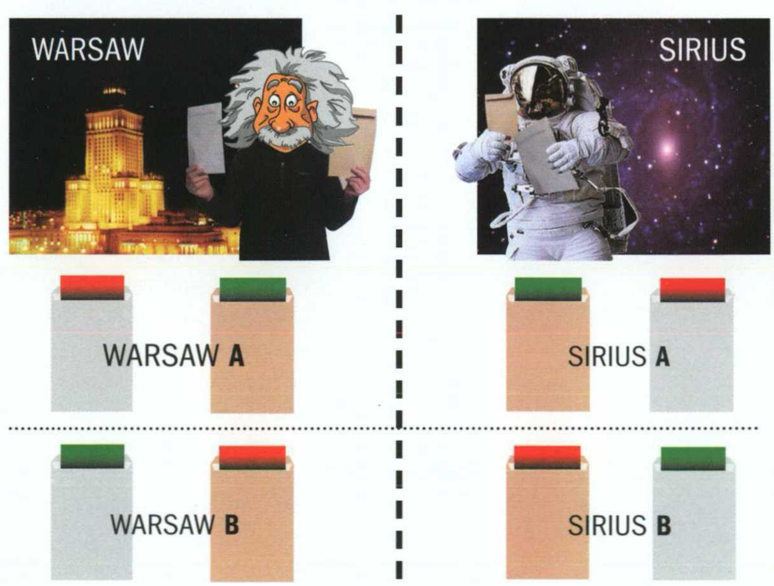
Einstein believed that quantum mechanics is not complete; that it must be complemented by additional "elements of reality". If we take two photons in a polarization singlet and check whether they have left or right circular polarization, the results will always be opposite. If one photon has left circular polarization, the second must have right circular polarization. Since the second photon can be at any distance from the first, the measurement on the first electron cannot affect it in any way (disturbances can be distributed at a maximum of the speed of light). According to Einstein, the second photon must have been in a hidden state defining for it the right circular polarization outcome from the very outset. This brings in an element of reality, expressing a hidden determinism.

From EPR to GHZ

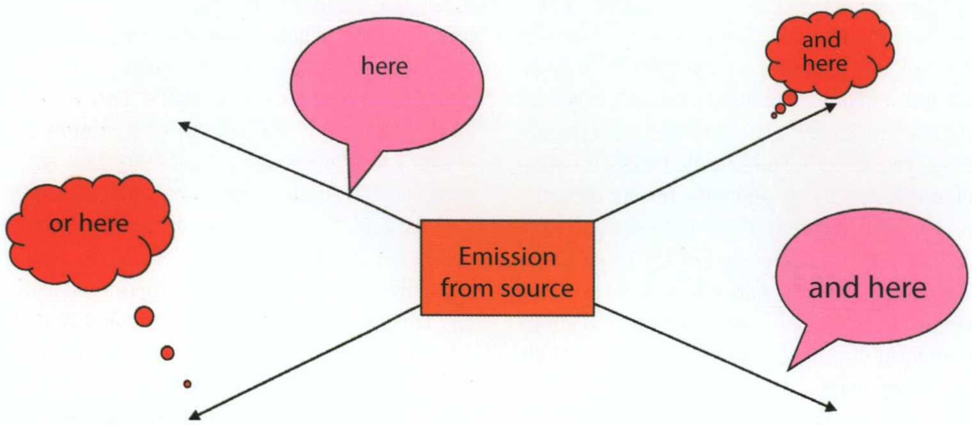
Claims of this sort one can find in an article by Albert Einstein, Boris Podolsky, and Nathan Rosen, in which they proposed a thought experiment contesting the Copenhagen interpretation, known as the EPR Paradox. In 1964, John Bell demonstrated that EPR's reasoning leads to contradictions of the type "one plus one equals zero", once we consider a broader range of measurements. Bell's Theorem excludes any supplementation of quantum mechanics consistent with local causality, which presupposes that events are determined by causes, and the range of influence of which is limited by the principles of distribution of disturbances according to the theory of relativity. This, in layman's terms, it means that if I sneeze in my kitchen in Gdynia, it can make me spill milk, but it cannot have the same effect on my cousin in Australia. However, if I sneeze while talking to my cousin on the phone, when the sound reaches him, he may also drop the mug he was holding...

It is impossible to produce computer simulations of the polarization of an individual photon from a singlet pair. If we were to replace the two photons with two supercomputers and load them with software of arbitrarily high sophistication, we would still be unable to recreate quantum correlations of a polarization singlet. This could only be achieved if we were to allow the computers to continually exchange information. However, according to the theory of relativity, distant photons travelling in opposite directions cannot exchange information. At most, they can carry information originating from a common source ("the software").

But does this paradox have observable consequences? This question gave rise to two-photon interferometry. The crowning achievement of this field came with the experiments conducted



"Entangled envelopes" in Warsaw and at a planet near Sirius. If we open them, both will always reveal cards of the same color, but the actual color is always random



Example of an entangled state: two photons of which we know only that they were emitted in two opposite directions (common property). Which of the two processes possible for the photons occurs? Fundamentally, this is impossible to establish without taking an additional measurement. However, such measurement would eliminate one of the possible indistinguishable processes! No two-particle interference due to entanglement would occur

by Alāin Aspect in 1981 and 1982. The question what happens if we take three photons was finally posed in 1989. At that time I was already working on entanglement. Daniel Greenberger, Michael Horne, and Anton Zeilinger (GHZ) demonstrated that when we shift from two-particle to tri-particle (or higher order) phenomena associated with entanglement, the paradoxical features of entanglement become even weirder than in the case of EPR. However, the problem was there were no tri-photon sources around, which could be effectively used in experiments.

During my first stay as visiting professor at the University of Innsbruck between 1991 and 1993, Anton Zeilinger and I resolved to find a method of observing tri-photon GHZ interference.

Photon interference, a short course

As long as it was believed that light is an electromagnetic wave, interference was understood as the result of superposition of waves. Where two waves "of the same phase" meet - peak meeting peak, trough meeting trough - oscillation is enhanced (greater light intensity); where waves meet out of phase - with peaks meeting troughs - there is no light (zero intensity). However, when we have just a single photon, interference must be explained differently, we use the function of the state of a form of two superposing waves. This means that there are some locations where the photon will never be detected (the two waves of the state function extinguish each other) and other locations where the probability of detecting the photon is greatest (the waves are in phase). The situation is seemingly the same, but it begs the question: with which of these two waves was the photon linked prior to detection? After all, we are only talking about a single photon, and it is always detected in full. Quantum theory is silent on the matter.

What if we were to use some devices which would allow us to detect with which wave the photon is travelling along? Unfortunately, any such attempt would end up in eliminating interference; this theoretical result has been confirmed experimentally. Quantum theory predicts interference only when the given final state (detection) can be reached by one of, at least two, possible different "paths". The paths must be fundamentally indistinguishable, that is the photon must not leave any detectable trace which could allow to distinguish between them (this is known as "indistinguishable quantum processes").

Two-photon interference manifests itself through coincidences: in changes in the probability of two distant detectors to register a photon each at the same moment of time. Such interference is at its highest when the state of the photon pair is maximally entangled: We can tune our experiment in such a way that we have zero probability of coincidence for a certain pair of detectors. This is also due to indistinguishability of relevant quantum processes, but there is no way to describe this as interference of waves.

Entangling the photons

In 1992, we came up with a trick allowing us to observe the GHZ-type interference, but first we used it to obtain entanglement swapping. How does this work? We start with two sources of entangled pairs and create two such pairs of photons. A single photon from each pair is sent to two interferometers, placed a great distance apart. The other two photons are directed to a central interferometer placed between the sources. Using narrow frequency filters and detectors with extremely sensitive temporal resolution, the photons lose their distinguishability in the central interferometer. Two detectors register a photon each, but the information on the source of the given photon is irretrievably lost. The related collapse of the two photon state in the distant interferometers leaves them in an entangled state, despite the fact that initially they were completely independent. This is how independent photons can get entangled.

The original method required an extremely high temporal resolution of the detectors. In autumn 1993, we replaced this requirement with pulsed "pumping" (or, activation) of the sources. With this feasible technique, in 1997 Anton's group in Innsbruck was able to conduct the first quantum teleportation experiment, obtaining GHZ correlations and the first entanglement swapping. These experiments were the beginning of the era of experimental multiphoton interferometry. Today we can observe interference of up to eight photons.

Together with Harald Weinfurter and Jian-Wei Pan's groups, we have also devised experiments for high contrast four-photon interference, and for six-photon interference with the group of Mohamed Bourennane. We have conducted the first observations of interference of photons originating from truly independent sources (with Zeilinger's group).

In 2000, we used numerical methods to demonstrate that non-classical phenomena are more robust for systems that can give a broad range of measurement results. This has overturned the myth that only systems giving yes-no results are significant. Earlier, we formulated operational foundations for observations of such phenomena. In an article I co-wrote with Harald Weinfurter in 2001 we presented a universal formulation of Bell's theorem. It can be applied in the analysis of interference experiments linked with polarization measurements on any number of photons.

Quantum information

The 1990s ushered in a period of intensive research on entanglement, and a new branch of physics was born: quantum information. Scientists are searching for new, non-classical, paradoxical quantum phenomena and their applications in the transmission or processing of information. This has resulted in new information transfer protocols, such as quantum teleportation or quantum cryptography, which are impossible with classical methods.

We have shown that entanglement allows us to reduce the exchange of information necessary to solve a certain broad class of computational problems. Together with Weinfurter's group, we tested the method experimentally; the same experimental system was then used to demonstrate an effective quantum method of secret sharing: Two individuals cannot use a cryptographic key generated using quantum methods without the permission of a third individual, who holds the key to their keys.

Our paper - whose first three authors were at some time my doctoral students - published in 2009 in *Nature* proposes the introduction of a new fundamental physical principle of "information causality": we demonstrate that the obvious fact that a message cannot provide access to a greater amount of information than the amount which is contained in the message itself (information is quantified in terms of the number of bits required to record it) makes it possible to pinpoint a certain fundamental property of entangled states. Information causality can be one of the elements of a set of natural principles implying quantum theory, theory which has hitherto not found any intuitive explanation.

Studies into entanglement were frowned upon until the early 1990s; they were a domain of opponents of quantum mechanics, including Bell himself. However, Einstein and Bohr's thought experiments eventually became possible. I was a "quantum mechanic" who belonged to a minority at that time, of those who interpreted Bell's theorem as a more profound expression of the paradoxical properties of the quantum world than Heisenberg's uncertainly principle. I joined the research shortly before the experimental and theoretical breakthroughs. ■

Further reading:

Zeilinger A., (2010). *Dance of the Photons: From Einstein to Quantum Teleportation*. Farrar, Straus and Giroux.

Pan J.-W. et al. (2012). Multiphoton entanglement and interferometry. *Rev. Mod. Phys.* 84, 777.

Gröblacher S., et al. (2007). An experimental test of non--local realism. *Nature* 446, 871-875.

Żukowski M., et al. (1998). Quest for GHZ states. *Acta Phys. Pol.* 93, 187.

Pawłowski M. et al. (2009). Information causality as a physical principle, *Nature* 461, 1101-1104.