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The Laureates of the Nobel Prize in Physics 2022

Some personal memories

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“Aspect’s Experiments” on Quantum Mechanics and Entanglement: a brief historical perspective

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The Laureates of the Nobel Prize in Physics 2022

The Nobel Prize in Physics 2022 was awarded to **Alain Aspect** (France), **John F. Clauser** (USA) and **Anton Zeilinger** (Austria) “*on the grounds of experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science*”. The results of their work paved the way for new technologies based on quantum information.

“Have you heard of Aspects’ experiments?” This question was one of the first asked by my new fellow students after I moved from Toulouse to Orsay university in September 1982. Leaving my native town was then motivated to prepare myself to follow master courses of theoretical physics in Paris. At that time I had been aware of the Einstein-Podolsky-Rosen (EPR) paradox and still remember my pride when I learnt that an experimentalist working at the Institut d’Optique d’Orsay succeeded in clearing it up.

Beyond the Einstein-Bohr debate on the completeness of quantum physics theory, the EPR paradox raised the fundamental question of our perception of reality. The “classical” concept of reality postulated that the state of a single particle (e.g., a photon) having interacted in the past with a second one could be measured *independently* of the latter over long enough separation distances. John Clauser, Alain Aspect and Anton Zeilinger experimentally showed that this property does not hold. Their successive demonstrations took many years of incredible efforts to dispose of the suitable lasers producing appropriate photon pairs and to build up the right setups overcoming the major loopholes inherent to the EPR “gedanken experiment”. This impressive work

led to award them with the 2022 Nobel prize in physics for proving the violation of Bell inequalities – thereby ruling out the existence of hidden variables by which two particles may remain “classically” connected to each other – and for pioneering practical applications of such “entangled” states in quantum information science.

The following articles, written by former collaborators of the Nobel laureates, nicely relate this heroic period in the recent history of science and further developments opening the fields of Bose-Einstein condensates, quantum teleportation and quantum computing.

The selection committee of the 2022 Nobel prize in physics recognized the soundness of the non-separability principle, indicating that nature should be non-local. Despite this seminal discovery we are, however, still missing a robust theoretical description of non-locality. The philosophical debate launched a century ago by Einstein and Bohr is thus not closed yet and goes on arousing numerous vocations in fundamental physics.

Luc Bergé, President of the European Physical Society

Some personal memories

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This Nobel Prize is a huge triumph for a field that was once so stigmatized.

Prologue

It is hard for young physicists today to imagine just how frowned upon it once was to discuss questions related to the foundations of quantum mechanics. The debates in the 1930s between the great old men, Einstein and Bohr, were considered to be purely philosophical and as having no influence on actual physics. We were told that Bohr was right and Einstein was wrong. David Mermin once coined the phrase “*Shut up and calculate!*” to summarize the Copenhagen-type views of that time.

In particular, the significance of the Einstein-Podolsky-Rosen (EPR) Gedanken-Experiment of 1935 [1] was not recognized at all. It was considered to be of no use and was entirely disregarded for about 30 years. I remember that in the early 1980s Abraham Pais, a distinguished physicist from Rockefeller University who had just published the bestseller “*Subtle is the Lord: The Science and the Life of Albert Einstein*” [2], told me: “*The EPR paper was the only slip Einstein made!*” How very wrong some judgements and prophecies within the field of physics can be!

In 1964, when John Bell was on sabbatical in the US, he had the leisure to reconsider the EPR case and he wrote the paper “*On the Einstein-Podolsky-Rosen Paradox*” [3], which contained Bell’s inequality. A Bell inequality, quite generally, is an inequality between expectation values of joint measurements of two parties, customarily called Alice and Bob, which all local realistic theories have to fulfil but is violated by quantum mechanics. We also speak of *Bell’s Theorem*, realized via Bell inequalities: “*Local realistic theories are incompatible with quantum mechanics.*” However, for a long time, Bell’s work did not arouse any interest.

John Clauser

The first person to become interested in the subject was John Clauser, a young postdoc from Columbia University, in the late 1960s. When he studied Bell’s inequality paper he saw that it contained a bound for all hidden variable theories – which he believed in – and he was fascinated and wanted to show evidence for it. So he planned to perform the experiment.

However, the value of experiments of this type was not recognized at that time. When Clauser had an appointment with Richard Feynman at Caltech to discuss an experimental EPR configuration for testing the predictions of quantum

mechanics, Feynman immediately threw him out of his office, saying [4,5]:

“Well, when you have found an error in quantum-theory's experimental predictions, come back then, and we can discuss your problem with it.”

Fortunately, Clauser remained resolute and was determined to complete the experiment. He wrote letters to David Bohm, Louis de Broglie and John Bell – all were declared realists – seeking advice or moral support. Let's quote Bell's reply [4]:

“In view of the general success of quantum mechanics it is very hard for me to doubt the outcome of such experiments. However, I would prefer these experiments, ... , to have been done ... Moreover, there is always the slim chance of an unexpected result, which would shake the world!”

Belonging to the rebellious Hippie generation of the 1960s [6], Clauser certainly *“wanted to shake the world”* [5], and in 1969 he sent an abstract to the Spring Meeting of the American Physical Society proposing the experiment. Soon afterwards, Abner Shimony called him and told him that he and his student Michael Horne had had very similar ideas. So they joined forces, and together with Richard Holt, a PhD student working with Francis Pipkin from Harvard, they wrote the famous CHSH paper [7], in which they proposed an inequality that was well adapted to experiments.

Clauser finally carried out the experiment in 1972, together with Stuart Freedman [8], a graduate student at Berkeley who received his PhD for this experiment. As pointed out in the CHSH paper [7], pairs of photons emitted in an atomic radiative cascade would be suitable for a Bell inequality test. Clauser and Freedman chose calcium atoms pumped by lasers, where the excited atoms emitted the desired photon pairs. The signals were very weak at that time, a measurement lasted for about 200 hours. For comparison with theory a very practical inequality was used, which was derived by Freedman [9]. The outcome of the experiment is well known: they obtained a clear violation of the Bell inequality very much in accordance with QM. This result was confirmed by subsequent experiments [10, 11].

Performing this experiment was truly a heroic act at that time; everything was self-made, not only the laser but also all the remaining equipment. Furthermore, Clauser could only work on the experiment because Charles H. Townes was intrigued by Clauser's ideas and offered him a job, half for Clauser's project and the other half for Townes' radio astronomy. Regrettably, because of this experiment, Clauser was not able to pursue an academic career. But it can be seen as redemption that he has now been awarded the Nobel Prize.

Alain Aspect

Alain Aspect, a young French physicist, was so impressed by Bell's inequality paper that he immediately decided to focus his Thèse d'Etat on this fascinating topic. He visited John Bell at CERN to discuss his proposal. John's first question to him was, as Alain later told me, *“Do you have a permanent position?”* Bell was so scared that it would ruin Aspect's career. Only after Aspect's answer in the affirmative could the discussion begin. Aspect's goal was to include

variable analyzers in the setup. In the early 1980s Aspect and his collaborators performed a whole series of experiments [12, 13, 14], with the result that the Bell inequalities used were significantly violated in each experiment. It was this that has now been recognised with the awarding of the Nobel Prize. An appreciation of Aspect's work can be found in a separate article.

Anton Zeilinger

In the 1990s, after Aspect's experiments, the physics community began to notice the importance and impact of such Bell-type experiments. Quantum information, communication and computation, centred around Bell inequalities and quantum entanglement, were gaining increasing interest. Now at last the prevailing attitude towards the foundations of quantum mechanics was changing. At the same time, the technical capabilities, the electronics and the lasers, were also improving considerably. Most important was the invention of a new source for creating two entangled photons, namely spontaneous parametric down conversion. Here a nonlinear crystal was pumped with a laser and the pump photon was converted into two photons that propagated on two different cones. On one cone the photons were vertically polarized and on the other horizontally. In the overlap region they were entangled. Such an EPR source was used by Anton Zeilinger and his group when they performed their celebrated experiments. But let me describe everything in order.

First of all, writing about Anton Zeilinger is a quite complex task. His accomplishments are substantial and influential in so many areas, not only in quantum physics and quantum information but also in teaching and in science administration. Zeilinger contributed to the popularisation of science – he is known by the public as *“Mister Beam”*. All of this, alongside his love for philosophy and art, makes Zeilinger an incarnation of a Renaissance Scholar. So I can only focus here on just some of his achievements.

Zeilinger's interest in physics was always driven by curiosity. Even in experiments that have made applications possible, his interest has been rooted in curiosity. Also notable is the courage he showed when, in around 1990, he switched from neutron to photon physics when he became a professor at the University of Innsbruck. This was, of course, not without considerable risk. But thanks to his unerring intuition in physics and also his charisma, Zeilinger gathered highly talented students around him with whom he performed fascinating experiments.

I first met Zeilinger in person in 1991 at the Cesena Conference [15]. We immediately found common interests and decided to work together. One of our aims was to educate the new generation of young physics students on the topic of Bell-like experiments.

In 1994 we established a course titled *“Foundations of Quantum Mechanics”* at the University of Vienna. Initially it took place in a small barrack in the old AKH (Allgemeines Krankenhaus - Vienna's former general hospital, now a campus of the University of Vienna) next to the so-called Narrenturm (fools tower), a notorious place. Anton and his group would visit from Innsbruck four times per semester. The students were required to jointly deliver a talk, supplemented by a

handout that would be distributed beforehand. There was always a break midway through the session, when coffee and homemade cakes would be served. It was in this cosy atmosphere that the Viennese students animatedly discussed the newest experiments being performed in Innsbruck.

Experiments which have since become famous were reported there first-hand, for example: Dik Bouwmeester, a member of Zeilinger's group, reported on "*Experimental quantum teleportation*" [16], and Gregor Weihs explained the Bell-type experiment "*Violation of Bell's Inequality under Strict Einstein Locality Conditions*" [17].

As you can imagine, the course became highly popular among the students and it continued running for about 25 years. It was undoubtedly one of the most influential courses at the Faculty of Physics in Vienna.

In 1999 Zeilinger and his whole team relocated from Innsbruck to the University of Vienna, where he became Professor of Experimental Physics. His debut was the famous experiment "*Wave-particle duality of C_{60} molecules*", which demonstrated the quantum mechanical interference effects by using big molecules such as fullerenes [18]. It opened up a new field of research, led by Markus Arndt, into interfering even much bigger molecules.

Next followed the "*Experimental test of quantum nonlocality in three-photon Greenberger–Horne–Zeilinger entanglement*" [19]. Back in 1989 Zeilinger had collaborated with Daniel Greenberger and Michael Horne (GHZ) and they had written one of the most influential papers in the field [20], commonly called the *GHZ Theorem*.

It was David Mermin, fascinated by this issue of non-local quantum correlations, who turned the original GHZ discussion into a gedanken experiment for a system consisting of three spin-1/2 particles. In his famous Physics Today article Mermin [20] gave an extremely clear and most comprehensible presentation of the GHZ argument, which still makes it appealing to the physics community nowadays. John Bell too, who had received a copy from Mermin, replied "*I am full of admiration for your 3-spin trick*" (private communication [20]).

The GHZ Theorem à la Mermin asserts:

"For a three spin-1/2 system there exists a physical situation where all local realistic theories are inconsistent and incompatible with quantum mechanics."

It is much more restrictive than Bell's Theorem which needs expectation values, i.e., the statistics of events. These three-particle entangled states, GHZ states, opened up the entanglement research for higher multi-particle states which are important for quantum computation.

Entanglement swapping is another amazing quantum feature which Anton and his colleagues had already discovered back in 1993 [21]. It is actually the teleportation of an entangled state. More precisely, given two pairs of entangled



Anton Zeilinger in his laboratory. Picture © Jacqueline Godany, IQOQI Vienna

photons, when performing a Bell state measurement for two photons of each pair, it instantaneously brings the remaining two photons into the same entangled Bell state. It was experimentally realized by Zeilinger's group in 1998 [22].

Even more amazing is the delayed-choice of entanglement swapping, where the order of the measurements is reversed as compared to standard entanglement swapping [23]. Here I became involved in Anton's activities as well and together with Walter Thirring and Heide Narhofer we were able to demonstrate that this phenomenon can be traced back to the commutativity of the projection operators of the measurements [24].

Before I continue to describe Zeilinger's experiments, I would like to mention that I also had the pleasure to collaborate with Anton on some other memorable events. In 2000, right after Zeilinger and his team had settled in Vienna, we organized a conference in honour of John Bell: "*Quantum [Un]Speakables I*" [25]. There we had numerous notable speakers, among them, just to mention a few: Mary Bell (the widow of John Bell), Gerard 't Hooft, Jack Steinberger, Roger Penrose, Alain Aspect, John Clauser, Anton Zeilinger (6 Nobel Prize winners so far), Roman Jackiw, David Mermin, Simon Kochen, Abner Shimony, Michael Horne, Daniel Greenberger, Nicolas Gisin, Helmut Rauch and others. In 2014 we organized a follow-up conference, "*Quantum [Un]Speakables II*" [26], where we had similarly distinguished speakers.

In the late 1990s there was an increasing amount of activity to test Bell inequalities. A record was set by Nicolas Gisin's group [27] in Geneva by using energy-time entangled photon pairs in optical fibers. They succeeded in separating their observers Alice and Bob by more than 10 km and could show that this distance had practically no effect on the entanglement of the photons.

In the new millennium a whole series of experiments was carried out, mainly testing the entanglement of particles at long distances via Bell inequalities. The vision was to be able, ultimately, to install a global network in outer space.

By further pushing at the limits of distance, Zeilinger's group set a record with an open-air Bell experiment over 144 km between the two Canary Islands, La Palma and Tenerife [28]. Zeilinger's former student Jian-Wei Pan and his group later extended the limit to 1120 km [29].

Up until 2015 the three loopholes: “*Locality, freedom-of-choice and fair sampling*” had only been closed separately in photon experiments. But Zeilinger's group succeeded in closing all three loopholes in one single experiment [30] (two other groups also achieved this, one in Boulder, the other one in Delft). Technically it was very challenging.

Furthermore, in 2018, an impressive “*Cosmic Bell test using random measurement settings from high-redshift quasars*” [31], whose light was emitted billions of years ago, was carried out by Zeilinger's group. This experiment pushes back to at least 7.8 Gyr ago, the most recent time by which any local-realist influences could have exploited the “freedom-of-choice” loophole to account for the observed Bell violation. Any such mechanism is practically excluded, extending from the big bang to today.

In collaboration with the Chinese Academy of Sciences, and in particular with the group of Jian-Wei Pan, Zeilinger and his team implemented quantum communication protocols between the satellite “*Micius*” and receiving stations on earth. The goal was to demonstrate a secure quantum key distribution. This key was used for the first intercontinental video call encrypted via quantum methods and demonstrated that a tap-proof quantum internet is possible.

Zeilinger also made fundamental contributions as a theorist and philosopher. Together with his student Časlav Brukner he developed a completely novel view of the meaning of a quantum state. According to their view, the quantum state represents “*information about possible future experimental outcomes*” [32,33]. Information is the most fundamental concept in quantum physics. The physical description of a system is nothing but a set of propositions together with their truth values, “*true*” or “*false*”. Amazingly, relying on a few information-theoretical assumptions, they were able to derive the characteristic features of quantum mechanics such as: coherence–interference, complementarity, randomness, the von Neumann evolution equation, and, most importantly, entanglement.



Discussion between Reinhold Bertlmann, Anton Zeilinger and Walter Thirring on the topic “*Zufall ist, wo Gott inkognito agiert*” (2013). Photo © Mirjam Reither

I was also able to share in Zeilinger's philosophical and religious view of the world in a discussion between Anton, Walter Thirring and myself, as shown in the photo. The discussion, titled “*Zufall ist, wo Gott inkognito agiert*” (*Randomness is where God acts incognito*), was led by Thomas Kramar, a science journalist, and appeared in the Austrian newspaper “*Die Presse*” (23.3.2013).

Zeilinger also attracted many highly talented students who went on to become distinguished professors in their own right, reminiscent of Bohr and his group in the old days. Weihs, Arndt, Brukner and Pan I have already mentioned, some others are: Thomas Jennewein, with whom Zeilinger performed quantum cryptography experiments [34], or Phillip Walther, with whom he investigated quantum computing [35]. In the middle of the 2000s he began working with Markus Aspelmeyer on the cooling of mechanical resonators by radiation pressure [36], a new field of research now led by Aspelmeyer.

Zeilinger has held several important positions within the science administration. For instance, he became Dean of the Faculty of Physics at the University of Vienna (2006 – 2009), an important step which enabled the implementation of a reform to the law concerning the organization of Austrian universities, which he also helped to shape. Furthermore, Zeilinger was director of the Institute for Quantum Optics and Quantum Information (2004 – 2013), and he became President of the Austrian Physical Society (1997 – 1998) and President of the Austrian Academy of Sciences (2013 – 2022), where he was the driving force behind many innovations.

Zeilinger initiated the founding of the Institute of Science and Technology Austria (ISTA), which is an international research institute for natural and mathematical sciences located in Maria Gugging.

In 2009 Zeilinger founded the International Academy Traunkirchen, which is dedicated to supporting gifted students in science and technology. The educational platform of this Academy includes lectures that are open to the general public, as well as workshops for students and courses for school pupils with talents in the natural sciences. In the summer months the Summer Academy in Traunkirchen runs courses for artists. I also had the great pleasure of organizing several workshops with Anton for the students of our University, where they had to work on various individual topics in quantum physics. At each workshop a renowned physicist was invited to speak, for instance, in 2012 the Nobel Laureate Serge Haroche explained his “*Schrödinger cat*” cavity experiments.

Aside from the Nobel Prize, Zeilinger has received numerous international prizes and awards. Mentioning all of them would be impossible here, but some prestigious examples are: the Micius Quantum Prize (2019), the John Stewart Bell Prize (2017), the Wolf Prize (2010), and the Isaac Newton Medal (2008).

Conclusion

The Bell inequality experiments of the last few decades have had an enormous impact on our view of reality. In my opinion, our perception of reality must be changed radically.

Objects have no properties before observation, in contrast to “naïve” realism, and the chronological sequence of observations is irrelevant.

Furthermore, nature is *nonlocal* as implication of Bell’s Theorem. But I think, precisely this *nonlocality* feature – which deeply disturbed John Bell since for him it was equivalent to a “*breaking of Lorentz invariance*”, what he hardly could accept – could be the key for a deeper and more comprehensive understanding of quantum physics.

All these experiments, which were performed for “philosophical” reasons, also triggered very practical applications, namely quantum information science, which is a prospering field today.

The Call

On Tuesday, October 4th, Anton Zeilinger was sitting at home, working on a paper that he and his group were due to publish. At 11 o’clock the secretary from his Institute called to tell him that there was a person on the phone who insisted on speaking to him but did not want to say why. The call came from a Swedish telephone number. When Zeilinger agreed to take the call, he found the Nobel Prize Committee on the line, who first assured him that “*It’s not a fake call*” and then told him that he had been awarded the Nobel Prize in Physics along with Alain Aspect and John Clauser. Anton was speechless, overwhelmed by this wonderful recognition of his work. It came as a shock, but very much a positive one.

Epilogue

On a summer afternoon in 1987, John Bell and I were sitting outside in the garden of the CERN cafeteria, drinking our late 4 o’clock tea. In this relaxed atmosphere I spontaneously said to him: “*John, you deserve the Nobel Prize for your theorem.*” John, for a moment puzzled, replied with seriousness: “*No, I don’t. ... it’s like a null experiment, and you don’t get the Nobel Prize for a null experiment. ... For me, there are Nobel rules as well, it’s hard to make the case that my inequality benefits mankind.*”

But, as it turned out, in 2022 the Nobel Prize Committee did indeed conclude that the violation of Bell inequalities was of benefit to mankind and awarded the Prize to Aspect, Clauser, and Zeilinger.

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“Aspect’s Experiments” on Quantum Mechanics and Entanglement: a brief historical perspective

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1. Introduction

Theoretical and experimental studies of the properties of light have been intimately associated with the birth and progress of Quantum Physics. It is well known that the whole story of “quantum light” began with Planck in 1900 and Einstein in 1905, and that a major impulse was given by the birth of the laser in the 1960’s. In this context, two theoretical works carried out in the 1960’s had a major impact on further developments in quantum physics: one by Roy Glauber (Nobel Prize 2005), which laid down the foundations of “quantum optics”, and one by John Bell, which paved the way for the experimental tests of the non-separability of quantum mechanics. Bell’s work contributed to solve a major debate on the very Foundations of Quantum Mechanics, opened by the famous article of Einstein, Podolsky and Rosen published in 1935. Alain Aspect has made major contributions to both subjects, and is also one of the founders of the research field known as “atom optics”, that is an extension of quantum optics from light waves to matter waves. In this article we will not present all of his work, but focus on experiments conducted at Institut d’Optique, in Orsay and then in Palaiseau, from the early 1980’s to the late 2010’s.

2. A short biography of Alain Aspect

Alain Aspect was born in 1947 in Agen, France. He studied at the Ecole Normale Supérieure de Cachan and Université d’Orsay, and got a degree in physics in 1969. After a master thesis in Optics in 1971, on Fourier Transform Spectroscopy by Holography, he taught during three years in Yaoundé (Cameroun), as an overseas service volunteer.

In 1974 he began a series of experiments on the foundations of quantum mechanics at Institut d’Optique (Orsay), known as “*Experimental Tests of Bell’s Inequalities with pairs of Entangled Photons*”. This was the subject of his PhD defense (Thèse d’Etat) presented in 1983¹, and the main topic for which he was awarded the Nobel Prize in 2022; more details will be given below. Later, together with his student Philippe Grangier he developed the first *source of single photons*, of a type now called “heralded single photons”. This allowed them to carry out a *single photon interference experiment*, which became a classic for textbooks to illustrate the wave particle duality, see also below.

From 1985 to 1992, he worked with Claude Cohen-Tannoudji at the Ecole Normale Supérieure (Paris) and Collège de France, on developing new schemes for cooling atoms with lasers. His main contribution was a method of *Laser cooling below the one photon recoil* by Velocity Selective Coherent Population Trapping (VSCPT). This new method allowed the ENS group to break the

so-called “single photon recoil limit”, and to demonstrate how this cooling scheme can be embedded in the general framework of Lévy statistics, predicting that there is no theoretical lower limit to the achievable temperature. This type of approach may be important for the development of optical clocks with trapped atoms or ions.

In 1992, he founded a new group of Atom Optics of the Institut d’Optique, which has moved in 2007 from Orsay to Palaiseau, on Campus Polytechnique. More details on the scientific achievements of the group will be given below by David Clément, one of his close collaborators on some of these experiments.

3. Orsay’s experiments: testing Bell’s inequalities and demonstrating single photon interferences

After the major work by John Bell in 1964 [1], an important conceptual development was the construction of a “testable” inequality by Clauser, Horne, Shimony and Holt in 1969 [2], and the proposal by Aspect in 1976 [3] to enforce Einstein’s relativistic separation between measurements, as also initially suggested by Bell [4]. Then there was a succession of increasingly sophisticated experiments, starting with the one carried out by Clauser and Freedman in 1972 [5], up to the three publications by Aspect, Dalibard, Grangier and Roger in 1981-1982 [6a,b,c]. All three experiments performed at Institut d’Optique used a very efficient source of entangled photon pairs, and the third one incorporated for the first time “time-varying” polarization analysers, all designed by Alain Aspect, and built by himself and his team.

The entangled photon source at Orsay was made from a Calcium atomic beam, resonantly excited to the upper level of a two-photon cascade by a Krypton ion laser and a tunable dye laser. Each excited atom decays by emission of

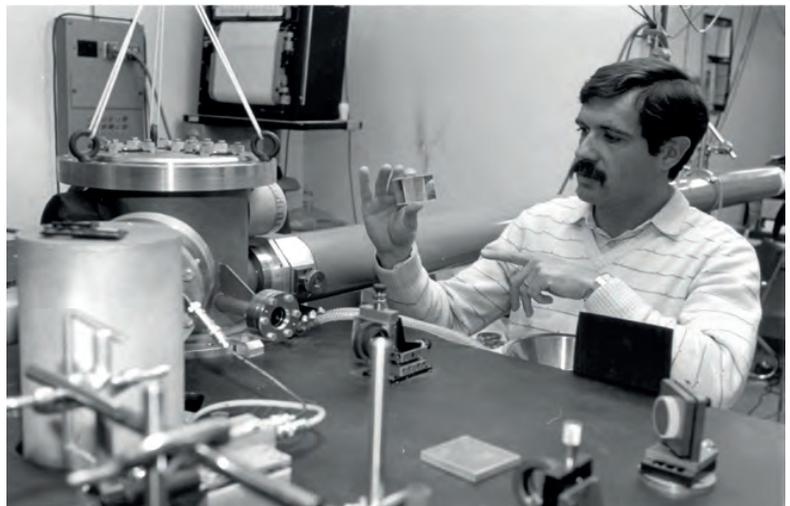


Fig. 1: Alain Aspect showing one of the multidielctric polarization beamsplitters used the experiments [6b] and [6c]. One sees also the atomic beam vacuum chamber where the Calcium atoms were excited up to the upper level of the two-photon cascade. Photo by Lars Becker-Larsen.

¹ Available at <http://tel.archives-ouvertes.fr/tel-00011844>

two photons at different frequencies, separated by a time interval corresponding to the exponential 4.7 ns decay time of the intermediate state. Due to the well-chosen angular momentum of the atomic levels, the pair of photons was emitted in the suitable entangled polarization state, as initially proposed and implemented by John Clauser in 1972. However, due to the laser excitation, the pair emission rate in the Orsay experiments was orders of magnitude larger than in Clauser's set-up. The first experiment [6a] used pile-of-plates polarizers like Clauser, but the second one [6b] used multidielectric polarizers (Fig. 1), that were combined with fast optical switches in the last experiment [6c].

The second experiment [6b] had a very high statistical accuracy and violated Bell's inequalities by more than 40 standard deviations, within a few minutes. Due to the more complicated optics the third "switching" experiment had lower count rates, but still achieved a convincing violation by 6 standard deviations. It is worth emphasizing that these violations did not result from iterative improvements, but were obtained at once, as soon as the actual experiment was performed, after a very careful - and very long - adjustment and control of all the parameters. Alain's students certainly remember this specific demand, not so easy to fulfill, but up to the stake of this fundamental test of quantum mechanics (Fig. 2).



Fig. 2: Jean Dalibard, Alain Aspect and Philippe Grangier at the Nobel Lectures for Physics in Stockholm, December 2022. Photo by Laurent Cognet.

In 1985 Alain Aspect moved to ENS, and Philippe Grangier inherited the entire Orsay setup, with the plan to carry out various experiments on single photon interference, this was the subject of his "Thèse d'Etat" under Alain's remote supervision. One idea was to use the Calcium atomic cascade to develop the first source of single photons, of a type nowadays called "heralded single photons". This work introduced a criterion for characterizing single photon sources that is universally used today. In order to fully illustrate wave-particle duality, the idea was to send these individual photons into a carefully designed and very stable interferometer, and to realize a true "single photon interference experiment", which became a classic for textbooks [14]. A few years later, another single photon source based on single nitrogen-vacancy center in diamond has been used in *quantum cryptography* [15a]. Also, in a collaboration with the group of Jean-François Roch, Aspect and Grangier participated to an experimental realization of the Wheeler's delayed choice

experiment [15b], in a scheme that is an evolution of the 1986 experiment.

On the Bell's inequalities side, many more experiments have been performed since the 1980's, confirming Aspect's results and leaving less and less room for "loopholes" (Zeilinger 1998 [7], Gisin 1998 [8], Wineland 2001 [9]). In addition, new non-locality tests were introduced, e.g. by Greenberger, Horne and Zeilinger [10], providing new perspectives and always confirming and reinforcing the initial work by John Bell. This series of work culminated in three "loophole-free" experiments published in 2015; a nice overview of the story is given by Alain Aspect in "Physics" [11]; see also the other article in this issue.

Parallel to these experiments, the new science of Quantum Information began to develop: scheme for quantum cryptography proposed by Bennett and Brassard in 1984, and relation to entanglement by Ekert [12]; first ideas on quantum computing (Feynman 1982); and finally "explosive" development after the introduction of the factorization algorithm using a quantum computer, proposed by Shor in 1994. A broad overview (in French) is presented in [13].

4. Atoms optics: interferences of matter waves and atom correlations

In 1992, Alain Aspect founded the group of "Atom Optics" of the Institut d'Optique, which in 2007 moved from Orsay to Palaiseau, on Campus Polytechnique. The name chosen by Aspect for this new group indicated the scientific direction he would follow for two decades: the study of the coherence properties of matter-waves and of optics analogs with atoms. Shortly after Aspect's return to the Institut d'Optique, a milestone was announced in 1995, the observation of Bose-Einstein condensation in a gas of atoms at JILA [16] and at MIT [17]. Bose-Einstein Condensates (BECs), realised with magnetically trapped atoms in three-dimensions (3D), appear when a macroscopic number of bosons occupy the lowest energy state of the trap. This situation can be seen as a matter-wave analog of photons stored in an optical cavity, the central building block of a (photonic) laser. By adding to the trapped atoms the equivalent of a partially reflecting mirror – that which let photons leak out of the cavity, Aspect, in collaboration with Philippe Bouyer, used the atomic BEC as a source to realise an atom laser [18]. The group then characterized the quality of the atom beam, in particular the presence of caustics transverse to the beam propagation, and they introduced a M2 factor defined in analogy to photon lasers [19].

At the same period, the phase of the atomic BEC matter-wave has become the object of intense study. Photon lasers are bright sources of light with a stable phase, well described by the coherent state introduced by Glauber. On the basis of the analogy with photon lasers, the problem of the phase of atomic BECs was raised rapidly [20] and the observation of highly-contrasted interferences between two BECs was reported [21]. These observations provided experimental confirmation of the coherence of 3D isotropic BECs. In contrast, Aspect and collaborators concentrated on elongated, quasi-1D configurations where the phase

properties are more subtle. In these elongated BECs, density fluctuations are suppressed but the phase can still fluctuate. Aspect's group produced strongly anisotropic traps using special electromagnets [22] where they were able to observe and characterise the phase fluctuations of quasi-1D BECs [23]. A program specifically devoted to the physics of 1D Bose gases was then initiated, with Christoph Westbrook and Isabelle Bouchoule, exploiting the technology of atom chips [24].

Alain Aspect's ability to identify important scientific questions and to launch himself enthusiastically into the study of new phenomena is exemplified by his works on the Anderson localisation. At the end of 2004, one of us (David Clément) started a PhD thesis with the aim to further probe coherence properties of elongated BECs. However, this plan changed a few weeks later, after Alain had discussed a new problem with Gora Shlyapnikov. The suggestion was to study the localisation of matter-waves in disordered potentials that results from multiple interferences, in analogy to the phenomenon introduced by Phil Anderson for electrons in a solid [25]. It was clear that the coherence properties of 3D atomic BECs allow interference phenomena to be studied. The interest of using atoms lay in the implementation of a well-controlled disorder and in the direct observation of the localised density profile of the matter-wave.

The group decided to shine the atoms with an optical speckle to produce a controlled disorder. Several properties of speckle fields were ideal for a controlled study of localisation phenomena [26] and Pierre Chavel, a colleague from Institut d'Optique, shared with the group his deep understanding of speckle. In the following years, the speckle disorder became a hallmark of Aspect's group in the cold-atom community. The first measurements of BECs expanding in a speckle disorder were obtained in 2005 [27]. Similar experiments were reported in Florence in Massimo Inguscio's group, initiating what Alain would have called a "*friendly competition*". These early experiments of the Orsay and Florence groups were not performed in a regime in which Anderson localisation could occur. Combined theoretical [28] and experimental developments finally led to the observation of Anderson localised matter-waves in 1D [29] (similar results in a bichromatic disorder were obtained in Florence [30]). This milestone was reached thanks to the synergetic effort of many people – including Laurent Sanchez-Palencia, Philippe Bouyer and Vincent Josse - whom Alain had enthusiastically brought together.

The Aspect group has made several landmark contributions to the field of atom optics, i.e. analogs of quantum optics experiments with atoms. In this context, a prerequisite for measuring correlations between atoms, similarly to Quantum Optics with photons, is the detection of individual atoms. At Collège de France, Aspect had already detected metastable helium atoms one by one, exploiting their large internal energy [31]. At Institut d'Optique, he built with Christoph Westbrook and Denis Boiron a metastable Helium experiment to explore Atom Optics. A major initial achievement

was the first metastable Helium BEC in 2001, which was a very risky experimental research because theoretical predictions had many uncertainties - but which finally succeeded in a spectacular way [32]. The group then pioneered an original approach to detect single metastable helium atoms in three dimensions with micro-channel plates. To describe this exceptional detector, usually used in accelerators and high-energy physics, Alain speaks of "*thousands of avalanche photodiodes in parallel*". Nowadays, this detection technique has become the workhorse of cold atom platforms using metastable Helium.

What makes metastable Helium atoms so special is that atoms are annihilated from the metastable state upon detection (decaying to their ground-state), just as photons are annihilated in the photodetection process. Therefore, atom correlations measured with the bosonic species Helium-4 are identical to those obtained in Quantum Optics with photons. Taking advantage of this analogy, the group observed the Hanbury-Brown and Twiss (HBT) effect with atoms [33]. But "*atoms offer more than photons*" and atom optics experiments can also be envisioned with fermions. This new possibility motivated Aspect and his collaborators to move their special detector to Amsterdam, where the group of Wim Vassen had brought the fermionic species Helium-3 to quantum degeneracy. This collaboration led to the detection of both boson bunching and fermion anti-bunching on the same apparatus, combining HBT measurements with Helium-4 and Helium-3 [34]. More recently, the group at Institut Optique focused on another landmark experiment in quantum optics, the Hong-Ou-Mandel (HOM) experiment [35]. The HOM effect is much more complex than HBT-type of effects as it reveals two-particles interferences. By exploiting the creation of momentum-correlated pairs of atoms, the group successfully realised an atomic HOM experiment [36].

The group founded by Alain Aspect has expanded over the years, to bring together six quantum gas setups led by seven permanent researchers and run by many PhDs and post-docs. A photograph taken at the announcement of the 2022 Nobel Prize in Physics gathers this vibrant group of people (Fig. 3).



Fig. 3: Photograph of the Atom Optics group founded by Alain Aspect taken soon after the announcement of the 2022 Nobel prize in Physics. Photo by Jean-François Dars.

5. Conclusion

To conclude, we emphasize that, in addition to his widely acclaimed talent as an experimentalist, the role of Alain Aspect as a charismatic speaker was essential in getting the importance of entanglement (or “quantum non locality”) widely recognized [1]. “Aspect’s experiment” has been an underlying motivation for many physicists to start working theoretically or experimentally on entanglement, especially in the 1980’s. Today, Quantum Information is a self-sustained research field, but this underlying motivation is still present, and the role of quantum entanglement is more important than ever.

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