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THE QUANTUM WORLD

Philosophical Debates on Quantum Physics

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Bernard d'Espagnat · Hervé Zwirn
Editors

The Quantum World

Philosophical Debates on Quantum Physics

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The Collège de Physique et de Philosophie

His research in theoretical physics, primarily dedicated to the conceptual foundations of quantum mechanics, and his participation in debates surrounding this question, gave Bernard d'Espagnat a very simple idea: that of creating a society whose aim would be "the in-depth study of the contributions of contemporary physics to the theory of knowledge, especially with regards to the degree of plausibility of different conceptions of reality (and of our relationship with it) that have been or could be considered". Thus the *Collège de Physique et de Philosophie* was created in 2010, whose founding members, alongside Bernard d'Espagnat, were Michel Bitbol, Jean Petitot and Hervé Zwirn. The aim of the *Collège de Physique et de Philosophie* is twofold: (1) to organize meetings where physicists and philosophers can explore the new ideas arising from the latest research, and (2) to inform the public through conferences and other suitable means of the ideas that are stimulating debate.

The Académie des Sciences Morales et Politiques

The *Académie des Sciences Morales et Politiques* is one of the five academies of the *Institut de France*. Its actions include the organization of temporary think tanks bringing together periodically, over a few months or a few years, a small number of

its members and external personalities for the study of a particular problem within its sphere of competence. Philosophy is one of them, which is why, aware of the advantages that exchanges between philosophers and physicists may bring to both parties, a think tank was set up to debate the possible contributions of recent research. Organized by the *Collège de Physique et de Philosophie*, these sessions were held at the Institute at irregular intervals between the end of 2010 and the start of 2013. The reader will find in this volume the transcript of these sessions.

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About the Editors

Bernard d'Espagnat after spending time at the *École Polytechnique* and a few years at the French National Centre for Scientific Research (CNRS) with stints abroad, contributed to the creation of the theoretical physics research group at CERN (Geneva) and conducted research in elementary particles physics. Professor at the Paris-Orsay University, he continued his research in this field while developing an interest in the conceptual foundations of quantum mechanics. He organized workshops on this theme in 1970 in Varenna (Italy) and in 1976 in Erice (Sicily) (the latter in collaboration with John Bell) focusing mainly on quantum entanglement and non-locality, which was then in the process of being verified experimentally, and which he subsequently investigated further. His main works are: *Conceptual Foundations of Quantum Mechanics* (W.A. Benjamin 1971), *À la recherche du réel. Le regard d'un physicien* (Gauthier-Villars 1979), *Un atome de sagesse* (Seuil 1982), *Le Réel voilé. Analyse des concepts quantiques* (Fayard 1994), *Traité de physique et de philosophie* (Fayard 2002). Member of the Institute (*Académie des sciences morales et politiques*).

Hervé Zwirn is a physicist and epistemologist, and a senior researcher at the CNRS (the French National Centre for Scientific Research). He is a visiting researcher at the Institute of History and Philosophy of Sciences and Technology (IHPST, Paris1, CNRS & ENS), at the Research Centre for Applied Maths (CMLA, CNRS & ENS Cachan) and at the Paris Interdisciplinary Energy Research Institute (LIED, CNRS & Paris 7). His research focuses mainly on the interpretations of quantum mechanics and their philosophical consequences, on the axiomatic formalization of inference modes and on the behaviour of complex systems. He also proposed a model of the theoretical decision-making process using the mathematical framework of quantum mechanics. He is executive director of the *Consortium de Valorisation Thématique de l'Alliance Athéna* (UMS 3599, CNRS & Paris4), responsible for the commercial development and dissemination of the research output in social sciences of French laboratories. His main books are: *Les Limites de la connaissance* (Odile Jacob 2000), *Les Systèmes complexes* (Odile Jacob 2006), *Philosophie de la mécanique quantique* (with Jean Bricmont, Vuibert 2009), *Qu'appelle-t-on aujourd'hui les sciences de la complexité?* (with Gérard Weisbuch, Vuibert 2010).

List of Participants

Alain Aspect, an experimental physicist in quantum physics, is a professor and researcher at the *Institut d'Optique*, a professor at the *École Polytechnique*, and a member of the *Académie des Sciences*. With his collaborators, he has conducted experiments on fundamental quantum mechanics: (1) with entangled photon pairs to test Bell's inequalities, showing that theories of local hidden variables must be abandoned, and (2) with single photons in Wheeler's delayed choice experiment. His other work has focused on laser-induced atom cooling with Claude Cohen-Tannoudji, on atomic quantum optics and on quantum simulators with ultracold atoms.

Michel Bitbol is a researcher at the CNRS at the Husserl Archives (ENS), Paris. He has worked on Erwin Schrödinger's philosophy of physics, and has presented a neo-Kantian interpretation of quantum mechanics. He became interested in the link between the philosophy of quantum mechanics and the philosophy of the mind, and developed a conception of consciousness inspired by the epistemology of first-person knowledge.

Oliver Darigol is a senior researcher at the CNRS, and a specialist in the history of science. He works in the Sphere Laboratory (CNRS/ Paris-Diderot University).

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Michel Le Bellac is an emeritus professor at Nice University. He has published many books including the textbook *Mécanique quantique* (EDP-Sciences/Éditions du CNRS, third edition, 2013).

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Introduction

A Journey through the Quantum World

In the past, science and philosophy were inseparable. Aristotle was at the same time a physicist, a logician, and a philosopher. Closer to us, Descartes, Pascal and Leibniz were as famous for their philosophical contributions as for their mathematical discoveries. Even more recently, Henri Poincaré was equally a mathematician, a physicist and a philosopher. However, the links between science and philosophy have become largely distended over the course of the twentieth century and the gap between scientists and philosophers has increased to the point that we can say that a certain wariness, even hostility, has developed between the two classes of intellectuals. It is regrettable for two reasons that are symmetrical in the sense that one deals with the genesis of scientific questions and the other with the answers that are provided. On the one hand, it is important to remember that the questions that scientists ask themselves are quite often derived from fundamental philosophical questions about the Universe. On the other hand, uncovering the profound meaning of the results obtained using scientific theories often requires that a philosophical light be shown on them. The dialogue between scientists and philosophers must be restored for the benefit of knowledge in the broadest sense of the term. In 1984, a pioneering initiative was carried out by the *Académie des sciences*. Under the direction of Jean Hamburger, the *Académie* hosted a series of talks on the philosophy of science, each followed by a discussion between scientists and philosophers[1]. It is with the same ideal in mind that the *Collège de physique et de philosophie*, under the umbrella of the *Académie des sciences morales et politiques*, decided to organize a series of sessions bringing together physicist and philosophers and dedicated in its vast majority to recent advances exclusively published in specialized scientific journals. The present volume is none other than the transcript of these sessions.

It has become apparent that modern physics, and quantum physics in particular, can shed new light on profound philosophical questions and anyone who wants to seriously consider fundamental questions about realism, determinism, causality or locality cannot ignore the contribution of physics. It is not so much that quantum physics provides definitive answers to these questions but it eliminates certain philosophical positions that are no longer tenable today. Conversely, the formalisms used by physicists raise difficult questions of interpretation that physicists themselves are incapable of solving without an in-depth philosophical reflection. The dialogue between physicists and philosophers benefits both parties. Philosophers must take into account the teachings of physics so as not to support positions refuted by current research and physicists can rely on philosophers to enrich their reflection regarding the very foundation of their discipline.

Underneath all the themes covered during our sessions, there was the question of knowing whether independent reality existed "*per se*". In the volume cited previously, Jean Hamburger wrote: "Scientific exploration of the world is limitless, but it is also without the hope of attaining a reality free from the observer, its methods and its observational scale". The themes of these sessions were also linked to the problem of causality and that posed by the notion of information. The positions of physicists and philosophers are far from being the same, but some of these positions are now inadmissible in the light of the recent results of contemporary physics. What are the coherent concepts at this time? What refinements must we bring to the notion of realism in order for it to survive? Must we expand the concept of causality to take into account the fact that a putative independent reality may have appeared first, before space-time? Must we consider that nature has chosen a behaviour that is indeterministic by its essence?

It goes without saying that in such a field, we were not expecting definitive and clear-cut conclusions. The aim was primarily to allow each participant, through these discussions, to expand his personal reflection relative to a field undergoing rapid changes. The purpose of this volume is, of course, to inspire its readers to do likewise. Admittedly, quantum mechanics has raised from its inception questions of a philosophical order. But the rediscovery in the 1960s of quantum non-separability and, more generally, of entanglement at a distance (notions which were demonstrated by Erwin Schrödinger as early as 1935, but which strangely enough remained unnoticed for 30 years) led to new discoveries, and at the same time shed new light on what we knew before. Thus it stimulated pure research (and even applied research: e.g. inviolability in cryptography, perspectives in quantum calculations, etc.), where notions of relationship, linked to the state of knowing (*software*), take increasing precedence over notions of atomicity, classically linked to the state of being (*hardware*).

This current state of things surely justified a collective reassessment—taking recent advances into account—of the different ways of conceiving the very notion of reality, as well as that of knowledge and the relationship between the two, as much those already conceived by philosophers (ancient as well as contemporary) as new ones which can now be considered. Admittedly, with this approach, we had to allow technicality to have its place but thankfully, as both philosophers and physicists were present, we naturally avoided the pitfalls of using technicality and erudition for their own sakes.

One remarkable thing in this field is the variety of expectations that physicists have regarding the information they acquire. It has not always been this way. It seems that in the era of so-called "classical" physics, everyone expected physics to lift the veil on appearances, in other words provide an ever-increasing knowledge of physical reality "as it really is in itself". A point that clearly emerged from our discussions was that nowadays, only a small minority of established physicists believe that this is actually feasible. Considering the prominent role gained by quantum mechanics with its achievements in predicting observations, and the difficulties in interpreting it as a description of reality that is radically independent of human beings, some take the extreme opposite view. They ask nothing more of their field than to help predict what will be detected following such and such procedure. Others do not abandon the idea of finding a descriptive component, but consider that it is exclusively centred on communicable human experience. Others only expect that a theory gives them "food for thought", ideas for new experiments, and assess its validity on that basis. There are also those who, while denying the reality *per se* of objects, persist in upholding the notion of reality, some linking it only to structures, i.e. to relations and not to what is being linked, whereas others consider it a hypothesis that is necessary but not experimentally verifiable for solving a contradiction: that inherent to the idea of a "universally relative" reality.

In the following pages, we will never see a specific interpretation presented at the outset by the speaker. That is because they, physicists for the most part, generally provide evidence for these implicitly and even reluctantly, with the feeling that giving them too much thought would force them to overstep the boundaries of their own field. What they present are consequently purely scientific theories, with supporting experimental evidence. But also—and how can it be otherwise?—with the surprises these bring that compel us to reconsider matters. The discussions that followed these presentations highlight the different ways in which each tries to overcome these surprises. Perhaps the main feature of this volume is to capture the way some fundamental conceptual problems spring, so to speak, from a physics not at all designed for this purpose by its practitioners. Thus, unsurprisingly, this collection of presentations and discussions does not present or justify a specific philosophically preconceived manner of interpreting the knowledge provided by contemporary physics.

We will not be surprised, consequently, by the diversity of opinions expressed implicitly or explicitly on this matter, or generally by the fact that no attempt has been made to classify by topic what was broached in the various chapters. This diversity is seen as something valuable to take advantage of. Consequently, this volume essentially presents the transcripts of the sessions during which such and such a theory or such and such an experiment was studied and discussed. Édouard Brézin, member and former president of the *Académie des sciences*, presented the inaugural session. Entitled "The inescapable strangeness of the quantum world", he reminded us that it is decidedly not by using our sole "clear and distinct" (Descartes) ideas that we can interpret our experiments in this field. And furthermore, we must abandon considering a number of these ideas as having universal validity. The following session (session II) consisted of the extensive debate, which arose from this reminder, between physicists and philosophers concerning the notion of reality. We can already see during this session, from the frank and direct interventions of Michel Bitbol, Carlo Rovelli and others, some of the crucial problems mentioned previously. Sessions III and IV were dedicated to the important notion of decoherence, which appeared in the 1970's and accounts for the fact that macroscopic objects can never appear to us in a quantum superposition (that a cat will never been seen alive and dead, to reprise Schrödinger's famous example). The former (session III) consisted mainly of a presentation by the physicist Jean-Michel Raimond of an experiment conducted by Serge Haroche, Michel Brune, himself and other members of the Kastler-Brossel Laboratory (*École Normale Supérieure*) during the 1990's; a milestone in this field, it was the first to show that decoherence takes place over a very short but finite period of time. The latter (session IV) gave an account of the very rich discussion inspired by this experiment, covering various theoretical aspects of decoherence, including all those aspects that, evidently, touch upon questions of general philosophy (and once again without eluding the questions relative to the notion of reality).

We know that in parallel to so-called "orthodox" or "standard" quantum mechanics—the one exclusively taught in all the world's universities—there is another theory, still thriving and seen as more satisfactory by some renowned physicists, called the "pilot-wave" theory, devised in 1927 by Louis de Broglie and developed from 1952 by David Bohm, which provides the same observational predictions as the standard theory while being based on radically different ideas. Examination of this theory was the central focus of sessions V and VI. The former (session V) was centred on a presentation—given by Franck Laloë, also of the Kastler-Brossel Laboratory—on the main principles of this theory and its advantages, the main one probably being that it provides a simple, not to say trivial, explanation of what happens during a quantum measurement: an effectively remarkable feature considering that the explanations given by standard theory of this process are still matter for debate. The latter (IV) gave an account of the discussion on this topic, as well as an addendum by Franck Laloë where he detailed the serious reservations he has regarding this theory.

Sessions VII and VIII covered two distinct topics, non-locality and the relational interpretation of quantum mechanics, topics associated here for circumstantial reasons: the recent publication of an article by Carlo Rovelli and Matteo Smerlak which re-examines the former in the light of the latter. Session VII consisted of a presentation by the second author, firstly on the main principles of the relational interpretation of quantum mechanics initially conceived by the first author, and secondly of its impact on so-called non-locality. The subsequent discussion was fed in part by contributions by Carlo Rovelli himself, who attended this session. As for session VIII, it consisted of two short presentations, one by Michel Bitbol on non-locality and Bell's theorem, and one by Alexei Grinbaum on the notion of the observer in Rovelli's approach, followed by a more general debate where other questions relative to this relational approach were raised.

Session IX was dedicated to a presentation by Roger Balian on the methods for resolving the measurement problem using a statistical interpretation of quantum mechanics, through the detailed analysis of certain dynamic models. To finish, prospects for future research were highlighted in the tenth and final session of this volume by Carlo Rovelli, who rapidly covered quantum gravity theory which aims to unify quantum mechanics and general relativity, and therefore attempts to provide a unified framework for the whole of physical phenomena.

It so happens that in French, many idioms of the spoken language evoke the essence of ideas faster and better than their counterpart in the conventional written language. For this reason, the language transcribed here has been modified to match the written form only to the strict minimum required. Whenever possible, and therefore as often as possible, their spontaneous form has been voluntarily preserved. We therefore have voluntarily preserved this conversational style to capture the mood of these sessions; this sometimes leads to frank clashes of opposing views. The point was not to give an illusion of a unity of vision. From this point of view, this volume is fundamentally incomplete. It is perhaps in this incompleteness—this absence of conclusion—that we will find its relevance. At a time of important conceptual upheavals, this volume may, by its very incompleteness, suggest new lines of inquiry, which are varied and supported by new and practically indisputable facts. It highlights as much the positives as the difficulties encountered with each of these and aims to promote a comparative in-depth analysis of these ideas. A difficult task that requires knowledge, circumspection and an imaginative intelligence to a very high degree, but which is for that reason promising and consequently likely to attract the best minds.

1. *La Philosophie des sciences aujourd'hui*, sous la direction de Jean Hamburger, Gauthier-Villars, 1986.
2. These sessions took place from November 22, 2010 to March 25, 2013.

Bernard d'Espagnat
Hervé Zwirn

Chapter 1
The Inescapable Strangeness of the Quantum World

Édouard Brézin

Bernard d'Espagnat. I am very happy to welcome you here, to this new working group entitled "Contributions of modern physics to the theory of knowledge" which you have all kindly agreed to participate in.

We will presently listen to Édouard Brézin, who needs no introduction especially here at the Institute as he presided over the Academy of Sciences for two years. I should nonetheless mention, very briefly, that his theoretical research has shed considerable light on the behaviour of condensed matter near critical points. However, not to worry, Mr. Brézin has no intention of lecturing you on this topic this evening. These are extremely cutting edge questions, and I think we will not reach such a high level of theoretical precision here, at least not during the first session! Mr Brézin is himself aware of this and has, on the contrary, kindly accepted to give an introductory presentation, which will be primarily an introduction to the questions we will discuss together, namely the highly conceptual questions regarding the relationship between physics and philosophy, in other words those touching upon the conception we may have of reality and what we mean by that. This is reflected in the title of his presentation "The inescapable strangeness of the quantum world".

1.1 Lecture by Édouard Brézin

First of all, I would very much like to thank Bernard d'Espagnat. It so happens that I attended his lectures on quantum mechanics as part of the Master of Advanced Studies in theoretical physics at Orsay, and it is therefore somewhat embarrassing

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for me to talk about quantum mechanics in front of you. And that for two reasons in fact, as, like all modern physicists, I am only a practitioner of quantum physics, and one that has never seen it wanting. However, I have no particular opinion on quantum mechanics. I simply went on to teach the subject, before handing over this role to Jean-Michel Raimond. What I have to say on quantum mechanics only pertains to common practice: I will try to highlight its complexity, not from a technical point of view, but through the intellectual questions it raises. Is there a need to recall Richard Feynman's famous saying on this matter? Feynman is a great hero of quantum mechanics as the formulation he introduced in terms of path integrals, without calling into question the ideas of the Copenhagen School, has nonetheless completely changed our view of quantum mechanics in the modern period. On the first page of his lecture on quantum mechanics, in volume 3 of his famous lectures [1], he wrote: "*Because atomic behavior is so unlike ordinary experience, it is very difficult to get used to it, and it appears peculiar and mysterious to everyone—both to the novice and the experienced physicist. Even the experts do not understand it the way they would like to, and it is perfectly reasonable that they should not, because all of direct human experience and human intuition applies to large objects*".

Quantum mechanics has led us into a strange world that is nevertheless our own. I will not cover the history of quantum mechanics. This would require lengthy presentations and there are people more qualified than me to do this. I would like to remind you that from the last quarter of the 19th century until 1926, the inability of classical physics to describe numerous phenomena was apparent everywhere. Let us mention for example the study of the emission and absorption of atomic spectral rays, a type of atomic music similar to the music of vibrating strings. There is an accumulation, an absolutely extraordinary "numerology" for classifying these rays. It was, as you surely know, one of Niels Bohr's greatest triumphs to completely explain this "numerology" for the hydrogen atom, for which he received the Nobel Prize in 1992. The official "birth" of quantum mechanics took place in 1900 with Max Planck's article on black-body radiation, i.e. the radiation of a heated body, which in classical physics is totally incomprehensible in many respects. Classical reasoning leads in effect to radiation continually increasing as the frequency increases, a divergence that is of course inadmissible. In addition, the experiments of Otto Lummer and Ernst Pringsheim (1894) clearly show that there is a complete contradiction between what we observe and classical ideas. Planck tried to resolve this by formulating a very complex hypothesis of "quantified energy levels" and "radiation quanta" that he spent a lot of time trying to justify, and which was only completely validated many years later by Satyendranath, Bose and Albert Einstein.

It seems to me, however, that the most serious crisis followed the discovery of the atomic nucleus by Ernest Rutherford in 1909. The atom became completely incomprehensible and its existence opposed itself violently to classical physics. In 1909, Rutherford discovered that there was at the centre of the atom a hard nucleus that makes up practically all of its mass. He calculated the size of this nucleus to be approximately 10^{-15} m. It is therefore an extremely small nucleus, if we recall that the size of electronic orbitals is around 100,000 times greater. Let us imagine what 100,000 times greater means. If we image that the nucleus takes up the entire room we are in, which is 10 m in length, then the electrons would be 100,000 times 10 m, i.e. 1000 km away. Between this room and the 1000 km where the electrons orbit, there is nothing. This means that our matter is empty. Why is it empty? (Note: it is empty in ordinary matter, but astrophysics describes very different types of objects, such as stars only a few kilometres in diameter with a mass as large as that of the Sun—neutron stars). However, the matter that surrounds us is nearly empty. Why is that?

In other words, why do electrons not lose potential energy by moving closer to the nucleus? Normally, in classical physics, a charged particle that orbits around a centre is endowed with non-zero acceleration, since only rectilinear motion is not accelerated. Yet all accelerated charged particles emit radiation and thus lose energy. This is what happens in accelerators designed to produce synchrotron radiation: the latter is produced by electrons that are maintained in circular trajectories contained within a ring. Why do electrons within atoms not radiate while losing energy and falling on the nucleus? This was completely baffling and Bohr's reasoning that allowed the calculation of the size of electronic orbitals and postulated this absence of radiation did not really provide any qualitative explanation. This came with Werner Heisenberg and Erwin Schrödinger.

Before I try to give an intuitive explanation, I will describe quantum physics in a bit more in depth. We must start with the notion of *state*. States should be seen as vectors, only they are not vectors in ordinary space. They are vectors in abstract space. The vectors in question here are objects that can be added to each other and can be multiplied by complex numbers. Let $|\Psi_1\rangle$ and $|\Psi_2\rangle$ be vectors; we obtain another vector by adding vectors $|\Psi_1\rangle + |\Psi_2\rangle$, or more generally $\lambda_1|\Psi_1\rangle + \lambda_2|\Psi_2\rangle$, where λ_1 and λ_2 are complex numbers. Quantum physics is formulated in this way: there is a linear structure in state space, which is not three-dimensional space, but an abstract space. Under these conditions, we can superimpose states and consider state $|\Psi_1\rangle + |\Psi_2\rangle$ or state $|\Psi_1\rangle - |\Psi_2\rangle$ in the same way we can speak of sums or subtractions of two vectors.

We must realize that straight away this hypothesis implies a representation that is extremely different from our classical view. To illustrate this, I will briefly describe how chemical bonds present themselves in quantum physics. Imagine that we have two positively charged nuclei and one electron. If these two nuclei are far apart, it is possible to have a left state where the electron is bound to nucleus 1, and also a right state where the electron follows the right nucleus. However, if the two nuclei are close to each other, there is in quantum physics a phenomenon that is not allowed classically, which involves crossing potential barriers, which we call *quantum tunnelling*. Let us consider the potential energy "seen" by an electron: in the vicinity of nucleus 1, it sees an attractive potential well, and likewise in the vicinity of nucleus 2; there is a barrier between these two wells. Classically, if the electron was located in the vicinity of nucleus 1, this potential barrier would prevent it from approaching nucleus 2. But, because quantum mechanics, as a result of its wave-like nature—I will of course return to this point—allows a wave to travel beyond the space where classical particles are confined, known in optics as an evanescent wave, the electron can transit from one nucleus to another. A basic calculation shows that the possibility to cross the barrier implies that it is the state $|\text{left}\rangle + |\text{right}\rangle$ that has the lowest energy. This is to say that the two nuclei are bound by this electron: the energy is lower when an electron is in the state $|\text{left}\rangle + |\text{right}\rangle$ than when it accompanies one of the two nuclei. This is the origin of the bond since energy would have to be supplied to return to the situation where the electron would accompany only one nucleus.

The two nuclei are bound by the electron, and they are bound by this impossibility, in the state $|\text{left}\rangle + |\text{right}\rangle$, to say whether the electron is left or right. It is completely delocalized, and it is that which underlies the electronic bond. It is that which acts in molecules where multiple nuclei bind. It is therefore not an esoteric phenomenon since it operates in all atomic and molecular chemistry. (The covalent bond only reiterates the same phenomenon for two electrons rather than one, with opposite spins.)

The evolution of states is as deterministic in quantum mechanics as it is in classical mechanics, meaning that if we know the forces present, then the state at time t can be deduced from the state at time 0 by a perfectly defined algorithm. The algorithm is called Schrödinger's equation in non-relativistic instances, and becomes Dirac's equation when speeds approach that of light. When there are phenomena of particle creation and annihilation, we must enter what we call field theory. However, the evolution remains perfectly defined there.

I will introduce straight away Feynman's point of view, which is essential for understanding the difference between classical and quantum mechanics. The evolution is characterized by Feynman by a sum of the *histories*. In classical mechanics, if we know that at time 0 a particle is located at the initial position x_{in} and that at time T it will be at the final point x_f, than its trajectory is defined: it is defined by a principle that we call the principle of least action, or in certain instances Fermat's or Maupertuis' principle, which allows the determination of a classical trajectory from an initial point to a final point. Action minimization is at work for example in the Snell-Descartes law of refraction. To give you an illustration, we can imagine a lifeguard on a beach who sees someone drowning. What will the lifeguard do to save the victim? He will take the trajectory that requires the least amount of time to get to the victim. However, he obviously runs faster than he can swim: the straight line from the lifeguard to the victim is not the one that minimizes the length of time. Indeed, it would be preferable to travel a bit further along the beach than along the straight line (towards the victim) where the lifeguard would have to swim more. The result for light is the Snell-Descartes law of refraction. In reality, this representation of classical physics shows that it is rather strange. Indeed, the lifeguard chooses his trajectory because he knows exactly where the victim is located. It is under these conditions that he can determine the trajectory that will take the least amount of time. However, light that travels from air to water, for example, does not know where the "victim" is. In a way we can say that, strangely, classical physics is not causal: how can light determine its trajectory if it does not know where to go? It so happens that the quantum point of view explains, and enlightens, this paradox. We are here within a framework where it is classical physics that is paradoxical and quantum physics that resolves this paradox [2].

Indeed, in Feynman's vision, we must not imagine that there is only one trajectory, the one that minimizes action. In quantum physics, all trajectories are possible: any *path* that goes from x_{in} to x_f over a time T is realized. And to find the probability amplitude (I will come back to what we call probability amplitude), the amplitude that allows us to characterize in a quantum manner the passage from an initial point to a final point over time T, we must add up all the histories. We associate a complex number with each history (forgive me for introducing equations). This complex number is the exponential of the action divided by a constant, which is the Planck constant. And to find the quantum result, we must imagine that the particle going from the initial point to the final point uses all these trajectories, and that, for each, we add this factor, this complex number, called "amplitude" $e^{iS/\hbar}$.

In the end we have the sum:

$$\sum_{\text{all trajectories}} e^{iS/\hbar}$$

In all macroscopic situations, this sum is dominated by classical trajectories. Allow me to explain this a little bit more intuitively: if I throw a stone in the water, this stone will create a wave that will travel. If I throw two stones in the water, then it is a bit more complicated. We can see there will be points where there will be crests because two arriving waves will coincide and there will be points where the two waves are opposed, one is in a crest whereas the other is in a trough, and there will be a flat area. This results in interferences, which are very easy to visualize with two stones. But imagine that you throw a billion stones, or rather a billion billion stones in the water without stopping. This will produce a lapping of waves that is so dispersed that in the end barely anything will move. This is what happens in Feynman's sum. When we are in a situation where the quantum effects are negligible, the interferences produced by adding these diverse trajectories balance each other out nearly everywhere. Only the "dominant" trajectory of this sum, which is the classical trajectory, will remain. Therefore, this non-causal view of classical mechanics, this view where we know in advance where we need to go if we apply the principle of least action, is only an appearance that results from the interference of non-classical paths. Causality is a lot more present in quantum mechanics than in classical mechanics.

I will now refer back to the well-known experiment in the quantum world of Young's double-slit experiment. The experiment consisted, as you know, of the following set-up: a first plate pierced by two slits is placed between a source emitting a coherent light beam and a screen. Thomas Young in 1801 used a light source, and by observing the interferences on the final screen, deduced the wave-like nature of light. However, it has been repeated with many other types of particle beams. Clinton Davisson and Lester Germer discovered in 1927 that, like light, electrons could diffract, confirming Louis de Broglie's prediction in 1924 (which they had no knowledge of!) of the wave-particle duality associated with all particles. Today, electronic microscopes routinely use this property of electrons of being equally waves and particles.

So, let us return to Young's quantum slit experiment: if we first block slit number 2 on the plate, we have a blot on the final screen centred on the geometric image of slit number 1. If slit 1 is blocked, we have a blot around the image of slit number 2. These are the two possible classical trajectories. But as you know, if no slit is blocked, the Feynman sum over these two histories results in an illuminance that is not the sum of the anterior illuminances (*please note that the Feynman sum is a sum of probability amplitudes; the probabilities, in this case the illuminations, are the squared modules of the amplitudes: the square of a sum is not the sum of all squares*). The resulting illuminance law can only be explained because the electron passes through the two slits. This interference experiment has been much commented on, particularly by Feynman. Nowadays it is carried out routinely. We can now send electrons one by one and observe the successive impacts dispersed randomly on the end screen. When we compile the results, we uncover an illuminance pattern with dense impacts zones and zones with no impact, an image none other than the interference fringes of Young's experiment. Feynman has analysed this experiment at length. In particular, he imagined putting a lamp behind the pierced screen between slits 1 and 2 in order to determine, since electrons interact with light, whether the electron passed through slit 1 or slit 2. However, as soon as we establish through which slit the electron went, the interference fringes disappear. We find ourselves in the same situation as when we throw classical marbles (i.e. under conditions where the wave-like nature does not manifest itself due to the smallness of the associated de Broglie wavelength). Feynman wondered if the disappearance of interferences was provoked by the radiation of the lamp, placed there to determine through which slit the electron passes, that *perturbs* the electronic wave by this interaction. He imagined that we try to minimize this perturbation; to do this, we need to illuminate the slits with a radiation with the longest possible wavelength: in this way the corresponding photons, which have an impulse that is inversely proportional to their wavelength, are extremely "nice" to the electrons and do not perturb them too much. Unfortunately, the moment we do this and when the wavelength of the lamp's radiation becomes in the same order of magnitude as the distance between the two slits, we can no longer distinguish the two slits and therefore we cannot determine if the electron went through slit 1 or slit 2. We must therefore conclude that the classical view that an electron passes through a single slit is wrong: the electron passes through the two slits. As before, the electron was left and right and we could not say whether it was left or right. This is the reality of quantum mechanics.

Heisenberg has allowed us to qualitatively understand many quantum phenomena. There are indeed two main origins of quantum mechanics: one that, following de Broglie, is implemented by Schrödinger who looked for the equation that determined the propagation of the de Broglie wave. Heisenberg followed an independent path by studying the rules of transition between atomic levels and he came up with an a priori unrelated *matrix mechanics*. Following on from Schrödinger, Pascual Jordan showed that the two points of view were identical. In 1927 Heisenberg discovered that within this mechanics, observables can be *incompatible*. He used as an example the position and momentum of a particle (the momentum, for low speeds compared to c, is the speed of the particle multiplied by its mass). In the same way—although the spin had not yet been discovered in Heisenberg's days—I will use the spin as an example: with each particle, for example an electron, is associated a type of internal vector that we call its spin, which like any good vector of three-dimensional space has three components: S_x, S_y, and S_z. These are the observables: we can theoretically measure each one of them: S_x or S_y or S_z. Yet these observables are incompatible, meaning that if we measure S_x, we must abandon knowing S_y or S_z, and vice versa. In the same way, if we accurately measure the position of a particle, Heisenberg explains why we must abandon knowing accurately the momentum of the particle. To explain this, he devised a thought experiment which we call nowadays *Heisenberg's microscope*: in order to know where a particle is, we need to "see" it and therefore interact with it. We can for example send a light beam on this particle and deduce its position from the effect of the particle on the beam. To localize it with an uncertainty of δx, the radiation wavelength must be smaller than δx; indeed, if the wavelength is greater than δx, we will only observe a diffuse image that cannot be "resolved" below this wavelength. De Broglie's relationship tells us that within this light beam, the photons that make up wavelength l have a momentum $p = h/\lambda$, the inverse of λ, to within a constant which is the Planck constant. If λ is too small to localize the particle, this means that the photons have a large momentum. (Note: this is why we build accelerators: to have good microscopes, we need short wavelengths; to have short wavelengths, we need large momenta. Large momenta, requiring much energy, cannot only be achieved by accelerators. Accelerators are, in a way, only gigantic microscopes. The LHC [3] is a microscope that allows us to go down to wavelengths in the region of 10^{-18} cm.)

Therefore, the photons that are used to localize the particle in question have a large momentum in the order of $h/\delta x$. Under these conditions, because their momentum is large, the collision between photon and particle will be very "hard", and that will result in a high uncertainty δp on the momentum of the particle that will be greater than $h/\delta x$. Thus the momentum of the electron, which we perhaps knew before measuring its position, for instance because it was at rest, becomes even less knowable the better we have measured its position. These two variables are therefore incompatible and the microscope imagined by Heisenberg provides a qualitative explanation for this. For a long time, we thought that the rather paradoxical nature of quantum mechanics, as seen in these incompatible observables that do not exist classically, was limited to Heisenberg's microscope. In fact, as we will show later on, the situation is far more complex than that.

Heisenberg's reasoning nevertheless explains why a measurement can change the state of the system. Furthermore, it allows us to understand qualitatively the previously mentioned mystery surrounding the size of atoms. Indeed, if the size of atoms decreases, if the radius of gyration of an electron around a nucleus decreases, this means, according to Heisenberg's reasoning, that it is better localized. The closer it gets (by thought experiment) to the nucleus, the better localized it is. However, if we improve our knowledge of its position, we decrease, as Heisenberg demonstrated, our knowledge of its momentum; kinetic energy, proportional to the square of the momentum, can then take on high values. Thus, thinking we are reducing potential energy, we are actually increasing kinetic energy. However, in the *fundamental* state, the electron actually minimizes the total energy: the sum of kinetic energy and potential energy. More precisely, potential energy $V = -\alpha/r$ effectively decreases when the electron gets closer to the nucleus. However, according to Heisenberg's reasoning, kinetic energy takes on typical values that are inversely proportional to the square of the localization length, which is in the same order of magnitude as the distance r from the nucleus:

$$T = p^2/2m = h^2/2mr^2$$

Therefore, he adds potential energy to kinetic energy, the former increasing as r decreases. Minimizing the whole provides an optimal length: the minimal r^* of the sum $T + V$ is not in the order of 10^{-15} m, i.e. the size of the nucleus, but 10^{-10} m, i.e. the size of the atom, since this sum reaches its minimum at:

$$r^* = h^2/me^2 \sim 10^{-10}\,\mathrm{m}$$

Therefore, the gigantic size of atoms, the astounding emptiness of our matter, results from the incompatibility of the observable position and momentum as illustrated by Heisenberg's reasoning.

The greatest mysteries of quantum mechanics stem from *measurement*. In quantum mechanics, the outcome of a measurement is random, and this randomness seems irreducible. We are no longer in the usual framework of using probability calculations as in classical mechanics. Indeed, classically, we often resort to probabilities because we are in the presence of extremely complex systems. If we want to describe the slightest gram of matter, the gigantism of Avogadro's number, in the order of 10^{23} particles in any grain of matter, prevents us from following the evolution of all the degrees of freedom. Consequently, we frequently use statistical or probabilistic calculations. However, this is only a theoretically convenient way to bypass enormous calculations. Besides, nowadays, the computing power of computers allows us to follow the movement of thousands of particles without the need for any calculations of a statistical or probabilistic nature. Nevertheless, the use of probabilities, of *statistical mechanics*, is in the end the best method for understanding the behaviour of matter. But let us repeat that the use of probabilities in classical mechanics is solely for the sake of convenience.

For a mathematician, the notion of probability does not pose any particular problem: a probability is a measurement of an ensemble. Thus for an alternative with 50% for one term, and 50% for the other, we know how to calculate the probability of the various possible outcomes without any problem. If we state that a coin has one in two chances of landing on tails, the probability calculation to land on tails 100 times for 200 throws poses no problem for a mathematician. For a physicist, it's completely different: the coin is a physical object and the probability assigned to it is just an estimate that relies on our knowledge of this coin. If we have no reason to believe the coin is biased, we will assign a priori a probability of ½, allowing ourselves to change our point of view if we notice when tossing that 50% does not fit. Note that the probability is not a characteristic of the coin; it is only a convenient way to bypass lengthy calculations. By tossing a coin, we could imagine modelling a priori the way it is thrown, the way it spins in the air, the way it falls on the table, and without doing any probabilistic calculation, we could try to deduce which side it will land on depending on experimental conditions. This is possible theoretically in classical mechanics, even if it is very complicated. In quantum mechanics, however, the notion of probability is of a different nature: it is irreducible; there is no way of avoiding the introduction of random variables. This will be illustrated below.

Let us come back to the electron spin, and the vector that is associated with it. The outcome of the measurement of this spin component along the z axis is either + or − within the units associated with the Planck constant. Thus, there are two possible values $\pm\hbar/2$, designated either by ± or by an arrow pointing up or down; two possible values and nothing more. This is already very different from classical mechanics, since if we measure the component of a vector along an axis in classical mechanics, the outcome, which depends on the angle of the vector with respect to the axis, can be any value between the length of the vector and its opposite. It is not like this in quantum mechanics. We must accept that this is the measurement outcome. There are more complicated things: if the state of the spin prior to measurement is state $|\Psi\rangle$, then after a measurement producing for example the outcome + along the z axis (+ means $+\hbar/2$), the state becomes an upwards state of the spin. The measurement has changed the state of the system. This does not seem extremely paradoxical in itself, if we recall Heisenberg's microscope: a measurement has perturbed the spin, but even so this immediately raises the question: what is a measurement? First of all, we find ourselves with two evolution principles. The first is the one we mentioned above; knowing the initial state, we can deduce the state at time t, for example by using Schrödinger's equation: $|\Psi(0)\rangle \to |\Psi(t)\rangle$. However, the measurement introduces a second evolution principle, called the *reduction postulate*, since if the state prior to measurement is $|\Psi\rangle$, after knowledge of the outcome, this state changes to $|\Psi\rangle \to |\Phi\rangle$. This raises the question of knowing when we should take a measurement, and what a measurement is.

Could we do without this second law of evolution which is specific to the measurement process? For this, we could try to describe the measuring apparatus as a complementary element of the physical world in question. We would thus consider the ensemble made up of (i) the system, which is initially in state $|\Psi\rangle$, (ii) the measuring apparatus, which is in state $|X\rangle$; we could try to describe the evolution of the state of the ensemble $|\Psi, X\rangle$, i.e. the electron/measuring apparatus ensemble. Is the evolution $|\Psi, X > (0) \rightarrow |\Psi, X > (t)$ of the ensemble, studied by a gigantic Schrödinger equation in which we include the evolution of the measuring apparatus and its coupling with the studied system, likely to explain the second principle, namely the reduction of the initial wave from the evolution equation? As we will see later on, the answer is probably no: the measurement process is not a stage that we can deal with in the same way as the studied system, using ordinary quantum dynamics. Is the random nature of measurement limited to Heisenberg's microscope, i.e. to the inevitable perturbation of the studied system by the measuring apparatus? Here as well, the answer is no, as we will see shortly.

Let me come back to the paradoxes that have not ceased to haunt quantum mechanics. Among the most famous are “Schrödinger's cat” and “Wigner's friend”, to use their now popular names. What is Schrödinger's cat? The well-known image was derived from discussions in which Bohr and Schrödinger distinguished themselves. The question was to know whether the strange nature of the quantum world could be transposed to the everyday macroscopic world. In order to do so, they imagined a radioactive particle; it is in an excited state prior to emitting its radiation, and de-excites after emission. However, it can be in one state or the other. For a given particle, it is well-known that it can be in one of the two states, or in any superposition of these two states. Schrödinger said: now imagine that this radioactive particle is in a box where there is cat. The box is sealed, we do not look inside; if the particle has disintegrated before the box is opened, than the radiation has killed the cat; if it has not, then the cat is still alive. Therefore the cat, like the particle, can be in two states: one state |live cat⟩ or one state |dead cat⟩, or still, as long as we have not looked inside the box, we can have superposition of states for the macroscopic object “cat” itself. Before opening the box to see the state of the cat, it can be in a superposition |live cat⟩ + |dead cat⟩. This seems absurd, much more so than a superposition of states for a particle. What can we make of this? I hope that Jean-Michel Raimond, who has carried numerous experiments on photon cavities, will tell us about certain explicit experiments that show how we go from a microscopic object to a macroscopic state. That is, here, the first paradox.

The second paradox is called “Wigner's friend”: when we open the box with the cat inside, we reduce the state |alive⟩ + |dead⟩ to the state |live cat⟩ or the state |dead cat⟩ depending on the state in which we find the animal. However, if Wigner's friend looks inside the box, and tells him the result only much later, at what moment must Wigner reduce the state of the cat? We are faced with the astounding conclusion that it is consciousness that produces the reduction. In this case, we have to introduce the observer's consciousness to carry out state reductions. This is very troubling, even more so when we apply quantum mechanics to the study of the primitive universe prior to the existence of any observer. What does consciousness mean in this case?

There is a way to resolve this, but I must tread carefully. Our colleague d'Espagnat has thought about this more than anyone else. There is no paradox, so it seems to me, if the state of the system, as part of the description of the system by the observer, corresponds to the observer's *own* subjective knowledge of the system.

In other words, as long as I have not carried out any observation, describing the cat in a state $|\text{live cat}\rangle + |\text{dead cat}\rangle$ is not surprising or paradoxical: it is my knowledge of the system, I describe it thus in the absence of an ulterior measurement that would lead me to change my description. (Allow me to mention the conversations with Rudolf Peierls in which he stated that there was no paradox if we considered that the state attributed to the system by the observer was only a reflection of his own knowledge of the system.) However, from this perspective, we do not really know where the physical reality is in this subjective description of the world. Does a physical reality exist independently of the observer? We would much prefer to be able to say that the reduction postulate related to measurement is a convenience that takes the place of a description of a complicated measuring apparatus. How satisfying it would be to think that if we included the measuring apparatus in the equations, we could avoid the problem of measurement and its subjectivity. However, as you will see, that is probably not possible.

Indeed, in 1935 things became considerably more complicated with a famous article [4], which at the time gained much interest from Schrödinger and Bohr who discussed it at length with Einstein, but which afterwards remained forgotten for a long time. When I was a young physicist, we generally thought that there was no difficulty, that quantum physics worked perfectly, that Einstein, Podolsky and Rosen (EPR) had dwelled on questions of no interest. It was only after the publication of John Bell's article in 1964 [5] that things changed and that the *EPR paradox* became once again the centre of much attention. EPR imagined a particle, for instance a positronium, which disintegrates into an electron and a positron; in a laboratory system where the positronium is at rest, the electron and the positron drift apart in opposite directions. Their spins, that of the electron and that of the positron, are in an *entangled* state, which we must describe. The emitted electron and positron both have spin; the conservation of the angular momentum (a consequence of invariance by rotation) implies that their spins, measured along any axis, are opposite. We can easily see what state $|+,-\rangle$ would be, where the electron spin is positive and that of the positron is negative; and equally for the state of opposite spins $|-,+\rangle$. However, quantum mechanics requires that these particles are emitted in state $|+,-\rangle + |-,+\rangle$, where we can no longer say what the spins are either for the electron or for the positron. Let us imagine that under these conditions a first investigator (nowadays conventionally called Alice) measures the electron spin and finds a positive outcome. This implies that the initial state of spin $|+,-\rangle + |-,+\rangle$ has been reduced through measurement to state $|+,-\rangle$. Consequently, after this measurement, which produced a positive outcome for the electron, we know with certainty that a second investigator (Bob) placed at an arbitrary distance from

Alice, and who has decided to measure the positron spin, will find a negative outcome. This appeared to EPR as extraordinarily surprising: Alice, by measuring, can predict from her measurement the outcome that Bob will find. There is no violation of relativistic *causality*, which postulates that no information can be transmitted at superluminal speed. When the experiment is over, the two investigators meet up. The list of outcomes obtained by Alice, as the experiment is repeated many times, is, let us say $\{+, -, -, +, -, -, -\}$; she knows that Bob will produce the opposite list: $\{-, +, +, -, +, +, +\}$. She does not need to look at the second list to know it. However, Alice can tell Bob afterwards what he will find only by ordinary means of information transmission.

For a long time, we considered that it was not that problematic. I will try to show you to what extent it is really surprising. (We are at the heart of the problem concerning knowledge.) In a certain way, we can superficially consider that the EPR situation is no more surprising than the following common experience: I arrive at my desk, I search my pockets, I find only a single glove, the right hand one; I therefore know the one I left at home is the left hand glove. Nothing paradoxical or mysterious: I know it straight away and if I want to transmit the information to someone at home, I can phone to say that the glove on the cabinet is the left hand one. However the following experiment is more complex: imagine that, before leaving their respective laboratories where they will analyse emitted twin particles, Alice and Bob agree that they will both measure the spin component along the x axis. Here, we know that if one finds +, the other will find—with certainty. But imagine that Alice, playing a trick on her colleague, measures the y component instead of S_x without telling him. Therefore she knows that Bob, who is still measuring S_x, instead of finding a well-determined outcome, will find with 50% probability $S_x = +$ or $S_x = -$. In other words, the effective outcome that observer 2 will find depends on what observer 1 is doing. It is a bit as if I said: if I am a magician and I can transform my right hand glove into a left hand glove, then I have also transformed the one at home from a left hand to a right hand one [6].

This implies that measurement is a non-local process. Once again it is not a violation of relativistic causality, it is a violation of measurement locality. Let us come back to what we were saying before: if I imagine that the measurement of the electron spin is an interaction between it and the measuring apparatus in Alice's laboratory, it will be localized to the ensemble "measuring apparatus/studied system". Now in the EPR situation, although the positron has travelled far, the measurement of the electron spin has also measured the positron spin. Therefore the measurement is not limited to a local interaction with a macroscopic apparatus. This tells us that, presumably, we cannot include the measuring apparatus in the studied system. If we included the measuring apparatus in the evolution equation, we would only put local interactions between the studied system and the apparatus. This non-locality of the measurement process shows that, presumably, it is not possible to leave out the second postulate of wave reduction. Nowadays, this experiment is carried out routinely with twin photons. (We even sell cryptography systems that rely on these twin photons; in optical fibres, the twin photons move kilometres apart. This thought experiment by EPR has now become a practical object that is used to know if communication between Alice and Bob has or has not been intercepted. This is known as *quantum cryptography*. If a spy has intercepted the communication, the absolute correlation between the polarization states of the twin photons is lost.)

One last point: are hidden variables a substitute for quantum mechanics?

Let us examine how quantum mechanics differs from classical mechanics. For example, we saw that the measurement of the spin along Ox and the measurement of the spin along Oy are incompatible variables. If we measure S_x, and the outcome is positive, the measurement of S_y is completely random and produces either + or − with equal probabilities. This is what quantum mechanics tells us. We could interpret this result thinking that it is the measuring apparatus that has modified the particle for which we have measured the spin. This modification would be such that, once we know S_x, then S_y becomes indeterminate, in the same way that once a position is measured, the momentum becomes indeterminate. Therefore, in this "naive" version of Heisenberg's vision, it is the measurement of S_x that prevents us from knowing S_y. However, we will see that the situation is even more complicated.

One way to "represent" this is to imagine that in reality, the electron population is made up, for example, of four types of particles: one where S_x and S_y are positive (+, +), one where S_x is positive and S_y is negative (+, −), one type (−, +), and one type (−, −). Four population types I call N_1, N_2, N_3, N_4. Thus the measurement of S_x will produce a positive outcome + with a probability that is the ratio of the number of favourable cases $N_1 + N_2$, the number of particles with a positive S_x, divided by the total number: $(N_1 + N_2)/(N_1 + N_2 + N_3 + N_4)$. After measuring S_x, I imagine that I abandon knowing S_y, because the measurement of S_x has perturbed the system too much. Let us note that we have stepped outside of the quantum framework by imagining these four population types, as this framework does not say that particles of the type S_x positive, S_y positive, etc., exist. It simply says that after having measured S_x the outcome for S_y is random, with equal probabilities. This limitation is not called into question by the principle of hidden variables, i.e. the replacement of the quantum description by the introduction of these four particle types which are not accessible to our measurements but provide a representation of the system. This seemed to be an alternative representation of the same physical facts.

For a long time, this interpretation went against quantum mechanics as the latter does not allow us to consider one of these types, such as S_x positive, S_y negative, since we cannot measure them simultaneously. Quantum mechanics insists on the fact that we can only conceive of what is measurable. It rejects the idea of a finer underlying reality that remains hidden because our measuring apparatus are too crude and violently perturb the system. Quantum mechanics claims that there is no finer reality. For a long time, quantum mechanics and hidden variables appeared as two points of view which were opposite but in a way equivalent in their practical predictions of measurement outcomes. We spoke of another interpretation of quantum mechanics. It seemed to be an alternative framework that was better suited for providing a more intuitive view of what was going on.

This ended a few years after the important contribution of an Irish theoretician, you (Bernard d'Espagnat), must have known him well at CERN, namely John Bell.