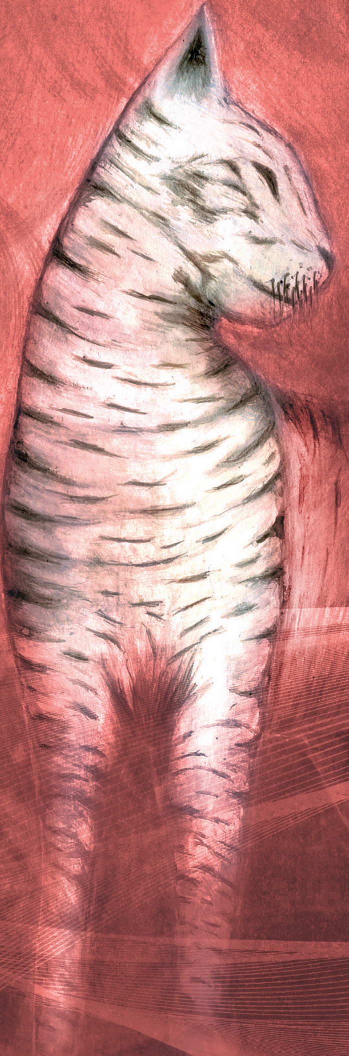
Interpreting quantum mechanics:
A historical approach



FAVIO CALA VITERY
ÉDGAR GUSTAVO ESLAVA CASTAÑEDA

UTADEO
UNIVERSIDAD DE BOGOTÁ JORGE TADEO LOZANO
FACULTAD DE CIENCIAS NATURALES E INGENIERÍA
DEPARTAMENTO DE CIENCIAS BÁSICAS

Interpreting quantum mechanics:
A historical approach

UTADEO
UNIVERSIDAD DE BOGOTÁ JORGE TADEO LOZANO
FACULTAD DE CIENCIAS NATURALES E INGENIERÍA
DEPARTAMENTO DE CIENCIAS BÁSICAS

Cala Vitery, Favio
Interpreting quantum mechanics: a historical approach / Favio Cala Vitery, Édgar Gustavo Eslava Castañeda. – Bogotá: Universidad de Bogotá Jorge Tadeo Lozano. Facultad de Ciencias Naturales e Ingeniería. Departamento de Ciencias Básicas, 2016.
154 p.; 21 cm.

ISBN: 978-958-725-182-1
1. Teoría cuántica. I. Eslava Castañeda, Édgar Gustavo. II tit.

CDD530.12"C141"

Fundación Universidad de Bogotá Jorge Tadeo Lozano
Carrera 4 Nº 22-61 – PBX: 242 7030 – www.utadeo.edu.co

Interpreting quantum mechanics: a historical approach

ISBN: 978-958-725-182-1
Primera edición: 2016

Rectora: Cecilia María Vélez White
Vicerrectora Académica: Margarita María Peña Borrero
Decano de la Facultad de Ciencias Naturales e Ingeniería: Isaac Dyner Rezonzew
Director del Departamento Ciencias Básicas: Favio Ernesto Cala Vitery
Director editorial (E): Jaime Melo Castiblanco

Coordinador editorial: Luis Carlos Celis Calderón
Diseño e ilustración de carátula: Samuel A. Fernández Castro
Diagramación: Mary Lidia Molina Bernal
Impresión: Panamericana formas e impresos S.A.

Impreso en Colombia
Printed in Colombia

Content

Favio Cala Vitery
Édgar Gustavo Eslava Castañeda

Interpreting quantum mechanics:

A historical approach

Reality favors symmetries and slight anachronisms.

Jorge Luis Borges.

-You´ve the loaf of bread there, on the tablecloth, says Johnny, looking at the air. It´s a solid thing, there is no denying it, it smells great and the color´s beautiful. It´s not me, it´s different, outside of me. But if I touch it, if I reach out my fingers and grasp it, then there´s something that changes, don´t you think? The bread´s outside me, but I touch it with my fingers, I feel it, I feel like it´s the world, but as I can touch it and feel it, then you can´t really say it´s something else, can you?

-That, my friend, is a question that every men with very long beards have been racking their brains over for thousands of years.

Julio Cortázar, "The pursuer"

Preface

Almost a century after the beginning of the quantum revolution, there still is a high level of controversy about the actual meaning of the theory. The living paradox is this: nobody has doubts about the predictive efficacy of quantum mechanics; however, no one seems truly convinced about having fully understood its physical meaning. Stated in different terms, while the world marvels with the technological developments the theory has allowed us to produce, think about lasers, semiconducting materials, imagery, computers, superconductors, nuclear energy, microwaves, etc., there is no consensus about some fundamental questions such as what is the world image revealed by quantum theory? Does it provide us, merely, with a picture of the world at the micro level? Does it make any sense to talk about a quantum image of physical phenomena?

This is an issue with no precedents in the history of physics. Even fundamental theories such as Newtonian mechanics, electromagnetism and general relativity were born in the middle of intense interpretative debates, from either metaphysical or conceptual tensions; but after some time and with the solid support of empirical evidence, and of the recurrent verification of their major predictions, all the apprehension about their proper interpretation where overcame. As a result, a unified image of the world seemed not only possible but already achieved, a universal idea about the nature and dynamics of the world, about the evolution of physical systems, that provides us with a clear image of what there is “out there”. An ontology for each theory.

Quantum mechanics is different. It introduces an uncertainty principle but falls short determining if such a principle is inherent to nature or introduced by the observers. That might be seen as the source of its problems. Something Einstein, Bohr, Heisenberg, Schrödinger, Dirac, Pauli, Bohm and many others spent a lot time and effort to elucidate.

This book condenses some of the critical features of the discussion about the interpretative problems of quantum mechanics, pointing out some possible ways out of the conundrum. In order to set the road for these matters, chapter one introduces a conceptual history of the theory and its alternative interpretations. Chapter two profiles a taxonomy of the interpretative problems and some possible solutions, focused in the so-called measurement problem. Chapter three questions the thesis of quantum mechanics becoming what it is due to historical contingency. Finally, in chapter four, an argument is advanced to consider one particular interpretation –the causal account- as an alternative view that may help with the solution of the interpretative knot.

The book has been written for a general audience, but the need for introducing some formal and mathematical elements, makes us recommend readers to have a basic knowledge of the theory.

1. Historical roots of the quantum interpretation

1.1 A history of two (and more) interpretations

Quantum theory was developed at the beginning of the 20th century as a mathematical formalism that allowed physicists predictive power over a series of experiments that seemed not to fit into the classical Newton-Maxwell descriptive frame. Spectral lines, radiation of heated bodies, and several other experimental puzzles made scientists recognize the need for a new set of principles to formalize the non-classical behavior of a large number of physical processes that challenged the classical models about the structure of matter and the nature of radiation. Planck, for example, right at the beginning of the century, had given in to a desperate hypothesis of packing energy in order to be able to accurately describe the black body radiation. Trying to save the stability of the atom, Bohr proposed small discontinuous jumps, destroying with it the idea that it was a miniature replica of a planetary system. And Einstein, with his explanation of the photoelectric effect, invited to think that radiation may have corpuscular properties. The formal synthesis of this catalogue of experiences came to life from two different routes: one, analytic, that led Schrodinger to propose a wavelike equation that describes the evolution of quantum systems, the other, positivistic, centered in empirical correspondence, would lead Heisenberg to develop his matrix mechanics. The mathematical correspondence of these two versions of the theory will later be demonstrated by one of them.

By the end of the third decade of the century, quantum theory was already established as a solid system for modeling the behavior of the world at the micro-level, becoming the interpretative framework of the dynamical evolution of micro-systems. In a word, it became quantum mechanics.

Quantum mechanics describes the evolution of a system by its so-called state function, a wavelike formula that contains the dynamical information of a quantum system at a given moment in time. According to quantum mechanics, the dynamical conditions of a physical system can be represented by means of the wave function that depends on the coordinates of the system (in an appropriate reference system) and on time. In other words, the wave function of a physical system describes the system's instantaneous state and its temporal evolution. The instantaneous state of the system is obtained from the solutions of the system's differential equations of motion for a specific time t, while the system's temporal evolution of a system is obtained by calculating the integral of the system's state function for a given time interval. Wave functions then constitute quantum mechanics' formal core.

In addition to its formal structure, a very specific definition of measurement serves quantum mechanics

> If the magnitude Q being measured has the value **q***i*, suppose that the associated pointer observable R reads **r***i*. Measurement then consists in establishing a physical coupling or interaction between the atomic system and the macroscopic measuring apparatus with the property that **q***i* gets correlated with **r***i*. Particular states in which measurement works in the way described are referred to as eigenstates of Q (Redhead, 1995, 34-35).

Measurements then are the bridges that allow us to correlate the reading of macroscopic apparatuses, such as ammeters, voltmeters and the like, with the states of the microscopic system under observation, by recording the micro-system's wave function state vector in the measuring device. This makes the question about the roles played by observers become a central issue; after all, it is observers who determine what of the system's variables are to be measured, who set experiments to establish the adequate coupling between macro and micro variables, and those who interpret and evaluate the measurement's results. A clear understanding of the kind of interaction that observers have with the quantum mechanical systems would help understanding the way in which measurement's results are related with the states they are said to represent.

According to some physicists, without observers there is nothing that can be said about the actual state of a quantum system, not beyond the fact that the system's behavior can be predicted by the probabilities associated with the system's wave function, something that is but an evident result of the formalism of the theory. But a definite determination that some particular state obtains requires the presence of observers that witness the state of the macroscopic apparatus used to make the measurement, a presence that, at the borderline between the macroscopic and the microscopic levels, seems to interfere with the processes that are taking place. According to others, there is no place for observers to interfere with the evolution of the states of physical micro-systems. Observations, measurements, are invasive only in the sense that without them we could never get any evidence for the existence of the behavior or the states predicted by the formalism of the theory. To say that the state of a physical system is altered by the presence of observers requires a further explanation of the specific kind of alteration produced by the act of observation that goes beyond the formal analysis of the physical processes involved. There is a difference between a physical event and our epistemic access to it, a difference that those who account of measurements in terms of observers, rather than merely in terms of what is observed, seem to forget.

This question about the role of the observers turned attention from the analysis of the mathematical fundamentals of the theory to questions about the theory's interpretation, both in its formal and experimental facets. By the late 20's and early 30's, questions about the metaphysical assumptions and ontological commitments of the theory began to play the same key role in the consolidation of the quantum mechanical paradigm that questions about the mathematical structure had played a decade before. In this sense then, issues about wave mechanics, experiments and measurement lead gradually to issues about the formulation and interpretation of the theory's formal and metaphysical core. In what remains of this chapter we will present a general view of some of the historically and conceptual most relevant interpretations of quantum mechanics.

The standard interpretation of quantum mechanics is known as the *Copenhagen Interpretation*, after the N. Bohr Institute's hometown, where a generation of physicists was introduced to the flourishing quantum view. According to the Copenhagen interpretation, what characterizes quantum mechanical systems is that they are permanently in a superposition of states, i.e., that their dynamical behavior, represented by their wave function, can be expressed as a linear combination of the wave functions that represent different states. In other words, if ψ_1 and ψ_2 are admissible wave functions of a quantum system, then any linear combination of then of the form $a\psi_1 + b\psi_2$, where a and b are a pair of arbitrary complex constants, is also a wave function of the system.

The Copenhagen interpretation of the behavior of quantum mechanical systems rests on three main principles: Von Neumann's principle, Heisenberg's Indeterminacy principle, and Bohr's Complementarity principle. Von Neumann's principle maintains that for each dynamical state of a quantum mechanical system (eigenstate) there is a definite probability (eigenvalue) that represents the possibility for finding the system in that state. This eigenstate-eigenvalue correspondence sets a limit between the actual state of any microscopic system and the knowledge we can acquire of it.

Heisenberg's principle formalizes such an inescapable indeterminacy in the outcome of any measurement by a correlation between pairs of dynamic variables of the system: $d\mathbf{p} = h/d\mathbf{q}$, where $d\mathbf{p}$ and $d\mathbf{q}$ are the momentum and position measurements of a quantum system such as a photon or an electron, and h is Planck's constant. This principle shows that when a measurement of one of the pair of variables takes place, the more we learn about it, the less we can know about its correlated companion. In other words, it shows that quantum systems are inherently indeterministic. Finally, Bohr's complementarity principle underscores the indeterminacy by showing that the only way to understand the nature of quantum mechanical systems is by acknowledging the intrinsic limitation imposed by the fact that the concepts that can be used to describe quantum systems depend on their detectable properties, defined by the measuring devices with which the systems interact (cf. Omnès, 1994, 160).

> The quantum theory is characterized by the acknowledgment of a fundamental limitation in the classical physical ideas when applied to atomic phenomena. The situation thus created is of peculiar nature, since our interpretation of the experimental material rests essentially upon the classical concepts. Notwithstanding the difficulties which, hence, are involved in the formulation of the quantum theory, it seems…that its essence may be expressed in the so-called quantum postulate, which attributes to any atomic process an essential discontinuity, or rather individuality, completely foreign to the classical theories… This postulate implies a renunciation as regards the causal space-time coordination of atomic processes. Indeed, our usual description of physical phenomena is based entirely on the idea that

> the phenomena concerned may be observed without disturbing them appreciably (Bohr, 1934, 88).

Every measuring act disturbs the system, making it impossible to get any precise information about the system's state immediately prior to the observation. Reality becomes definite only when observations are made, and it is precisely this dependence upon observers that separates classical from quantum systems. Bohr insisted in making this very clear.

> The very nature of the quantum theory forces us to regard the space-time coordination and the claim of causality, the union of which characterizes the classical theories, as complementary but exclusive features of the description, symbolizing the idealization of observation and definition respectively. Just as the relativity theory has taught us that the convenience of distinguishing sharply between space and time rests solely on the smallness of the velocities ordinarily met with compared to the velocity of light, we learn from the quantum theory that the appropriateness of our usual causal space-time description depends entirely upon the small value of the quantum of action[1] as compared to the actions involved in ordinary sense perceptions (Bohr, 1934, 89-90).

Therefore, any attempt to formulate a physical theory that integrates classical and quantum systems must account

1 Bohr is referring to Planck's constant $h= E/\nu$, where $E=$ energy, $\nu=$ frequency. Planck (1900).

for the existence of such a borderline and develop an interpretation that includes both sides of the border, each one in its own particular terms. Both quantum mechanics and classical mechanics should be considered complete physical theories in the qualified sense that each one says all that is possible to say about the physical systems they study. Each theory describes a distinct domain, one classical and one quantum, but this does not make them incomplete. They are complementary levels of explanation of physical phenomena.

The problem of trying to determine what happens at the borderline between measured systems and the measuring apparatus is the Copenhagen version of the so-called Quantum Measurement Problem (QMP). On one hand, the quantum formalism establishes that the result of the interaction that occurs during a process of measuring is the superposition of the physical states of both the observed system and those of the measuring device. Measurement puts both the targeted system and the measuring device into a superposition state, making any talk about determinate pointer readings of the measuring apparatus as meaningless as talking about the existence of unmeasured microphysical states. The indeterminacies that characterize the quantum level become part of the world at the classical level. On the other hand, as experience teaches, it is always the case that determinate pointer readings are obtained whenever we make a measurement. Regardless of the superposition that the formalism demands, observers never encounter superimposed pointer states, only a determinate pointer's position. The question of where exactly the collapse of the wave function takes place, of where exactly to set the boundaries between quantum and classical systems, is left unanswered by Bohr and the rest of the members of the Copenhagen school, although its consequences are a central part of their interpretation.

Not happy with the results of this way of partitioning the physical world, different groups of physicists opposed the Copenhagen Interpretation and offered alternative interpretative frameworks aimed at undermining the principles in which the standard interpretation rests: completeness of the theory, linearity of the temporal evolution, and collapse of the wave function. Doubtless the most famous of such critical alternatives is the one advanced by Einstein, Podolsky and Rosen, in a now classic paper (Einstein, Podolsky and Rosen, 1935). The EPR paper, as it became known, states that the existence of specific values for the dynamical variables of a physical system is as real for quantum mechanical systems as it is for the classical ones, regardless of the accuracy of the measurements or the very possibility for making such measurements. This realist understanding of the dynamic variables stands in an open contradiction with Bohr's conclusion that after suitable interactions between a measuring device and a physical system "neither the measured observable nor the pointer readings have determinate values" (Bub, 1997). By contrast, Einstein, Podolsky and Rosen state that the mere possibility of measuring each variable requires granting the existence of properties corresponding to the variables. Consequently, descriptions that deny the existence of dynamical variables, as Bohr's interpretation does, have no place within physics.[2] According

2 There are different interpretations of the possible meaning of "realism" for Einstein. For extensive discussion of this issue, Fine (1986), Ballentine (1972), and Shimony (1981) are excellent information sources.

to EPR, the objective reality of a physical system is independent of our selection of the theoretical frame we use to interpret it, and it must be clearly distinguished from the concepts that those theories use to represent the systems. As a matter of fact,

> The elements of physical reality cannot be determined by a priori philosophical considerations, but must be found by an appeal to the results of experiments and measurements… We shall be satisfied with the following criterion, which we regard as reasonable. If, without in any way disturbing a system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity (Einstein, Podolsky and Rosen, 1935, 777).

The heart of the EPR paper is to make the case for a situation in which it is possible to determine experimentally definite values for a pair of complementary variables. The structure of the EPR thought experiment goes like this: after showing that measurements of a two-particle system can be made without disturbing the system, the authors apply their criteria of physical reality to the outcomes of some possible measurements, as they are allowed by the formalism of quantum mechanics. The resulting situation is that the measurement's outcome obtained for one of the system's particles grants knowledge, though indirect, of the corresponding variable of the second particle. The authors conclude that, since the completeness of quantum mechanics is incompatible with their notion of physical reality, the completeness hypothesis has to be dropped to do justice to the experimental results.

The experiment[3] consists of a molecule composed of two atoms with spin +/-ħ/2. From an initial zero spin state the molecule disintegrates as a result of a process that leaves unaltered its total angular momentum, making its atoms separate from one another until their mutual interaction becomes negligible. Because spin is conserved in the splitting process, the total spin of the system, the sum of the spin of the two atoms remains zero at every moment after the initial splitting. The significance of the experiment becomes clear once we consider how quantum mechanics describes measurements of the dynamical variables of the system, of the molecule's distant atoms. Such a measurement shows that if we find that the spin component in a specific direction of one of the atoms is, say, -ħ/2, we can then infer that the spin component of the second atom (in the same direction) is, because of the conservation condition, +ħ/2. Given that the measurement of the first atom has in no way disturbed the second one, the inferred value fulfills the conditions for being considered an element of reality. Thus, the process described by the experimental arrangement implies the possibility for obtaining a definite measurement outcome of the dynamical variables of both spatiotemporal ends of the system, a result that undermines the standard interpretation of quantum mechanics.

3 We use Bohm's modified version of the experiment (Bohm, 1952) rather than the original version because it is more intuitive than the original presentation and makes the conclusions easier to understand. As a matter of fact this is the reason why the EPR experiment is usually presented in Bohm's version.

The EPR authors' conclude that the explanatory difference of classical and quantum systems and the way this difference affects the possibility of making sense of unmeasured phenomena is not something that rests on the nature of the quantum mechanical systems but on our deficient understanding of their behavior. By holding that unobserved phenomena do not exist until they are registered by a measuring device, quantum mechanics generates an explanatory gap between observed and unobserved phenomena. Of course,

> One could object to this conclusion on the grounds that our criterion of reality is not sufficiently restrictive. Indeed, one would not arrive at our conclusion if one insisted that two or more physical quantities can be regarded as simultaneous elements of reality only when they can be simultaneously measured or predicted. On this point of view, since either one or the other, but not both simultaneously, of the quantities P and Q can be predicted, they are not simultaneously real. This makes the reality of P and Q to depend upon the process of measurement carried out on the first system, which does not disturb the second system in any way (Einstein, Podolsky and Rosen, 1935, 780).

Such is the EPR's version of the quantum measurement problem, a problem the authors consider can only be solved by re-interpreting quantum mechanics in accordance with the principles of objective reality, the independence of physical reality and measurement, they present in the paper.

Otherwise, one ends up having an incomplete theory, as it is the case with Copenhagen interpretation, one that does not account for every element of physical reality. The EPR interpretation of quantum mechanics then, while still adhering to the principle of linearity, rejects the completeness interpretation of the theory because it implies an undesired dependence between the act of measurement and physical reality, as expressed by the supposed collapse that takes place at the measurement moment.

Bohr replied to EPR's criticism promptly (Bohr, 1935, 145-152) pointing out that the EPR authors failed to understand the nature of quantum systems and, consequently, transferred the indeterminacy from the systems to the physics used to describe them. Quantum mechanics is not incomplete but a complete theory that describes a world whose rules are different from those of the classical world. Bohr's major concern with the conclusions of the EPR paper is that the thought experiment it rests on offers inadequate support for the incompleteness interpretation because of an ambiguity in the notion of physical reality. Such ambiguity is exposed by acknowledging that the necessary non-disturbing character of the measuring procedures is at odds with the role they play in the very definition of "physical reality," in particular of the dynamic variables of the system.

The point stressed by Bohr is that, even granting that there is no mechanical disturbance in one of the molecule's atoms caused by measuring the other atom, such measurements determine the type of predictions that can be made about the distant partner of the measured atom. In the case of the two-atom molecule, the measurement of one atom's spin in the, say, x direction determines that the only valid predictions we can make about the second atom have to be stated in terms of its x-spin. Bohr understands the fact that the EPR authors omit acknowledging such a trivial result as an example of a fundamental problem with the customary causal account of physical phenomena, a problem that can only be overcome by a "radical revision" of the foundations of our definition of physical reality. Naturally, Bohr sees that the Copenhagen interpretation is the only route towards the must needed revision. A renunciation of the 'customary account of causal phenomena' is central in Bohr's case for the completeness of quantum mechanics. Instead of pointing out a problem with the theory, what the need for a new account of causal relations does is to emphasize the need for a physics that recognizes that physical phenomena are complex sets of observers, systems under observation, and experimental arrangements that make observation possible. There are no unregistered, unmeasured, phenomena.

From this standpoint the problem with the EPR argument is that its thesis about the incompleteness of quantum mechanics is based on a wrong definition of physical reality. EPR's mistake rests on its use of a physical principle that, although natural and functional for classical systems, do not apply in the realm of quantum entities: the independence of physical reality and measurement. But the lesson to learn from the complementarity principle is that physical theories must be restricted to their own domains. What constitutes the principal difference between classical and quantum-mechanical descriptions of physical phenomena, declares Bohr, is not the limitations of their particular perspective but the difference between the regions of the physical world where they are effective. In the case of measurements, the difference amounts to a difference between the limits they establish between the regions of a system that has to be considered part of the measuring instruments and those considered the objects under investigation (Bohr, 1935).

Obtaining an all-inclusive physical description of the classical and the quantum worlds would be a matter of summing up classical and quantum physics, after recognizing their contextual validity. Unless such recognition takes place, it would be impossible to understand that quantum mechanics is complete because it tells us all that is possible to be known about the micro-world. Quantum mechanics is at least as complete as classical mechanics is complete, inside the limits of its own concrete, microscopic, context. W. Pauli expresses this tension in terms of the limitations in the language when he writes that

> While the means of observation have still to be described in the usual 'common language supplemented with the terminology of classical physics,' the atomic 'objects' used in the theoretical interpretation of the 'phenomena' cannot any longer be described 'in a unique way by conventional physical attributes.' Those 'ambiguous' objects used in the description of nature have an obviously symbolic character (Pauli, 1948, 307-308).

The measurement problem is then the inevitable result of non-quantum observers crossing the boundary to measure events in the quantum world, while still limited by their own perspective, their "common language." The significance of this boundary is reflected by the difference in theoretical formalisms needed to describe each domain and by the different answers each theory gives to the question of what is real in the world.

As part of his attempt to support Einstein's incompleteness interpretation and trying to clarify the terms in which the Bohr-Einstein dispute should be understood, E. Schrödinger proposed an experimental scenario that made evident that the indeterminacy of quantum systems can have observable consequences for macroscopic events. According to Schrödinger, formal models are tools that provide information about the behavior of physical systems; they enable us to develop "expectation catalogs," predictive rules of the temporal evolution of physical systems.

Apart from the actual observation of a system's set of variables over a period of time, there is nothing we can say about the system but that its temporal evolution is described by certain probabilistic wave functions, regardless of whether it is a classical or a quantum system. As a matter of fact, for both quantum and classical systems, unobserved phenomena exist in an indeterminate fashion, as probabilities, and the act of observation makes probabilities collapse into concrete observed pointer readings. In this light, then, the measurement problem that arises at the borderline between quantum and classical systems is nothing but the expression of the differences in the epistemic access that observers have to the system's state. It is precisely to stress this situation that Schrödinger's well-known cat experiment was conceived.

> A cat is penned up in a steel chamber, along with the following diabolical device (which must be secured against direct interference by the cat): in a Geiger counter there is a tiny amount of radioactive substance, so small, that perhaps in the course of one hour one of the atoms decays, but also, with equal probability, perhaps none; if it happens, the counter tube discharges and through a relay releases a hammer which shatters a small flask of hydrocyanic acid. If one has left this entire system to itself for an hour, one would say that the cat still lives if meanwhile no atom has decayed. The first atomic decay would have poisoned it. The Ψ-function of the entire system would express this by having in it the living and the dead cat (pardon the expression) mixed or smeared out in equal parts (Schrödinger, 1935, 157).

The (macroscopic) cat trapped in his closed environment has a 50% probability of being alive and a 50% of being dead after a certain amount of time, the same probabilities the microscopic, radioactive material has for decaying or not decaying. The indeterminacy originally confined to the microphysical level turns into a macroscopic one, making the final state of the macroscopic system, the cat, correspond to a superposition of macroscopically different states, being dead or alive, as is the case with the states of microscopic systems. Surprisingly, and this is the heart of the measurement problem from Schrödinger's perspective, while there is no way for any external observer to eliminate the microscopic indeterminacy, the macroscopic indeterminacy is never observed, as the possibility of making direct measurements on the system evidences.

In the case of the cat-in-the-box experiment, the consequence of the measuring operation is a dramatic disturbance in the observed system that makes the cat's 50/50 live/death probabilities collapse into either a dead cat or a living cat. All the pre-measurement probabilities become definite outcomes of the measurement act, with the disturbances generated by observation affecting not only the microscopic system's final state but also the spatiotemporal vicinity of the measuring devices. The fact that observation, measurement, generates such dramatic changes is a situation without parallel in classical systems. In this context, the quantum measurement problem can be understood then as:

> To say exactly what constitutes a measurement of a quantum-mechanical observable, and then to explain how is it possible for a properly conducted quantum-mechanical measurement always to yield some definite outcome. This is a problem, because plausible attempts to say in purely quantum mechanical terms what constitutes a measurement interaction apparently imply that properly conducted quantum measurements do not always yield some definite outcome (Healey, 1998, 54).

As a result, two different situations, contradictory in a sense, but definitely related to one another, define the new state of affairs. On one hand, there are the state functions of a system, the maximal knowledge's catalogs of the system's past and present states. Such catalogs are far from perfect; they are just maximal in the already explained sense of saying as much as it is possible to ask from them. In this sense Einstein is right about quantum mechanics being incomplete. It is incomplete because quantum mechanics is just a model, and any model is a limited descriptive device, even a maximal model as is the case with QM. On the other hand, the disturbances introduced in the system's state by the measuring process make it impossible to hold the non-disturbance approach needed to complete successfully EPR's attempt to describe a future state of the system. The unavoidable disturbances preclude the complete accuracy of any judgment about the system's future. In this sense, Bohr is right: the theory is complete because it tells us all that can be said about a system's state and evolution. Asking for more would be unjustly forcing quantum mechanics to go far beyond its scope.

Schrödinger resolves the dilemma about the completeness of quantum mechanics not by choosing one side of the debate but by recognizing both the limitations of our descriptions and the consequences of our participation as observers for the systems under scrutiny. After all, declares Schrödinger, "there is a difference between a shaky or out-of-focus photograph and a snapshot of clouds and fog banks" (Schrodinger, 1935, 327). In Schrödinger's hands, the measurement problem becomes a problem about our theories, about their scope, limits, and applicability, not about the constitution of the world. It is an epistemic, not a metaphysical problem. It is in this sense that Schrödinger's conclusion sides him with Einstein's incompleteness interpretation.

A close relative to the Incompleteness interpretation of Einstein and Schrödinger is the *Hidden Variables* interpretation, which postulates "the existence of hitherto unobserved and presumably unobservable physical quantities whose evolution under suitably designed laws exactly determines the outcome of the individual quantum processes" (Torreti, 1999, 374). The principal defender of the hidden variables' cause is David Bohm. Bohm developed an interpretation that leads to the same predictions for measurement outcomes that those of the standard interpretation but that avoids what he considers the main problem of the previous interpretations: the implicit assumption that what quantum mechanics is about is not the physical world but our knowledge of quantum systems' states. According to Bohm, all that is required for his new interpretation is to grant some non-problematic assumptions about the phenomenology of quantum systems. The first assumption is that the wave function of the quantum mechanical system evolves in accordance with Schrödinger's equation, or that it preserves the standard interpretation's notion that the temporal evolution of the wave function of an individual quantum mechanical system is deterministic. Second, we assume that the particle's momentum equals its one-dimensional speed gradient i.e., we are operating in a one-dimensional probabilistic space. Third, we recognize that we are dealing with a statistical ensemble, and we cannot control the precise location of any individual subsystem of the ensemble. With these assumptions as a cornerstone, Bohm develops a theory of measurement that re-interprets the physical content of Schrödinger's equation in terms of some hidden parameters that permit descriptions of the evolution of single-particle systems out of an initial probabilistic configuration.[4] These hidden parameters determine the

4 Over the last fifty years Bohm has restated his interpretation in diverse ways, naming it "causal interpretation" (Bohm 1974) and "ontological interpretation" (Bohm and Hiley

result of particular measurements in such an intricate and uncontrollable way that, for all practical purposes, descriptions of quantum systems have to be made only as statistical correlations between the values of the hidden variable and the directly observable result of measurements. This is the reason why we are unable to determine experimentally the precise position and momentum of quantum systems. Consequently, Bohm sees the uncertainty principle "not as an inherent limitation on the precision with which we can correctly conceive of the simultaneous definition of momentum and position, but rather as a practical limitation on the precision with which these quantities can simultaneously be measured" (Bohm, 1952, 383). This makes conceivable, at least in principle, the existence of measurements that violate the uncertainty principle.

From the hidden variables standpoint, then, quantum mechanics is incomplete, but in a different sense from that of Einstein and Schrödinger. Instead of blaming the formalism for obscuring our view of the quantum world and for using a doubtful criterion for physical reality, Bohm posits an unknown mechanism, the Hidden Variables, and holds them responsible for the non-classical behavior of quantum systems. Quantum mechanics is incomplete because it has not found yet the basic mechanism that governs the evolution of quantum systems, a mechanics that rests on "unpredictable and uncontrollable disturbances" created on the observed

1993). The idea of the restatement is to make the interpretation more inclusive, in the sense of extending its consequences to a broader set of events, from merely quantum mechanical systems to macroscopic and ultimately the universe as a whole. Given that the core of the interpretation has not been dramatically modified, in the remaining of the chapter we use the "original hidden variable" version. (Bohm, 1952).

system by the measuring apparatus. This has a dramatic consequence for the theory of measurement.

> The essential new feature of quantum measurement is that there is mutual and irreducible participation of the measuring instrument and the observed object in each other. As a result, any attempt to discuss this process as measuring 'a property of the observed object alone' will not be consistent with our interpretation. Rather, we say that the result of measurement is a potentiality of the combined system and can be determined only in terms of the properties of the particles, along with the wave function of the combined system as a whole (Bohm & Hailey, 1993, 97).

As a result, Bohm's quantum measurement problem is not a problem with the ontological commitment of the theories, not a problem of what counts as "real" as Einstein states it is. It is also not an epistemic problem, a feature of the content and scope of current empirical claims, as it is for Schrödinger. Nor is it the expression of an irrefutable feature of the quantum world, like Bohr thinks it is; it is not a matter of what is "real" as Einstein insists, nor a problem of epistemic character, a feature of the content and scope of our empirical results as Schrödinger would defend. Neither is it the expression of an irrefutable feature of the quantum world, as Bohr wants us to believe. The measurement problem is an empirical problem, the result of our actual lack of understanding of the intricate nature of the composite systems of measured objects and measuring devices. Such a problem is to be solved by further empirical testing and a mathematical analysis that acknowledges the inescapable unity of this "undivided wholeness". In our final chapter we will have more to say about this approach to the quantum theory.

The final interpretation we will refer in our historical survey is the *Relative State* Interpretation. Originally introduced by H. Everett (Everett, 1957), and developed later by B. DeWitt (DeWitt, 1970 & 1971) and N. Graham (Graham, 1973), the relative state interpretation targets the problem that, although formally quantum systems are a superposition of state vectors, in practice there is always only one outcome for a particular variable measurement. In other words, the relative state interpretation was designed explicitly to solve the quantum measurement problem, as it arose from the Copenhagen interpretation.

Like the Copenhagen interpretation, the relative state interpretation regards quantum mechanics to be complete. However, it distances from Bohr's by considering the collapse of the state's wave function an unnecessary result of the formalism, due only to the incorrect interpretation of the role that Bohr and others assigned to observers in the evolution of quantum mechanical systems. Everett's departing point is to consider the whole universe as a closed system that evolves deterministically in accordance to Schrödinger's equation. Consequently, instead of having the split between observer and object that characterized both the Copenhagen and the incompleteness interpretations, Everett sides with Bohm by denying the existence of a classically separated reality, and the observer/observed relative independence, as well as the wave function collapse that this independence imposes. However, unlike Bohm, the relative states interpretation maintains that the result of any possible measurement actually takes place, but that we are limited to live in a world where only one of those multiple possibilities is actually witnessed. Thus, instead of asking for the result of some particular measurement's outcomes, Everett uses the relative states interpretation to solve the question of how to apply quantum mechanics to the universe as a whole, to the 'space-time geometry itself' (Everett, 1957).

The key concept of Everett's interpretation, the notion of relative state, asserts that the states of the subsystems of a composite physical system are never independent of the state of the composite system as a whole. In other words, there is no sense in which a subsystem can be said to be in a well-defined state, independent from the larger system it belongs to. A state of any subsystem will always be relative to the state of the remainder of the composite system. Every observation creates a new pair of correlated subsystems an observer/observed subsystem and a subsystem consisting of the rest of the universe. It follows that observers play a central role in the relative states interpretation because they determine how a subsystem's configuration is established. As a matter of fact, in Everett's view, observers, physical systems capable of recording the measurement outcomes, determine the interaction's outcomes between measuring apparatuses and systems under observation.[5] The observation makes the observer enter into a superposition of states that characterizes the system being observed, making it impossible to determine the state of the

5 A criticism of this notion of observers as memory keepers is the theme of Bell (1984, in Bell. 1987, 93-99).

observer after his/her observation. Subsequent observations create historical (temporal) records of a subsystem's evolution, with the consequence that every new observation is determined, in part, by the results of previous observations. Thus, measuring a system locates an observer in a world where one of the possible measurement outcomes occurs.

> We thus arrive at the following picture: throughout all of a sequence of observation processes there is only one physical system representing the observer, yet there is no single unique state of the observer. Nevertheless, there is a representation in terms of a superposition, each member of which contains a definite observer state and a corresponding system state. Thus, with each succeeding observation (or interaction), the observer state 'branches' into a number of different states. Each branch represents a different outcome of the measurement and the corresponding eigenstate for the object-system. All branches exist simultaneously in the superposition after any given sequence of observations (Everett, 1957, 459).[6]

Each measurement then dissolves the previous independence between the state of the system and the state of the observer, entangling them in a superimposed, inseparable unit. However, the entangled state still represents a particular eigenstate of the combined system. The combination of these two situations makes DeWitt conclude that the entangled

6 This is why the relative state interpretation is also known as the Many Worlds interpretation.

state represents the world shared by observers and observed systems; the only world in which the particular measurement that defined their relation took place. It is in this sense that Everett's remark that the quantum mechanics formalism is capable of yielding its own interpretation should be understood (DeWitt, 1970, 33).[7] Therefore, because there is never a collapse of the state vector of the universe as a whole, this interpretation does not face a measurement problem along the lines of the alternative interpretations. Measurements are not a special category of physical interactions, they simply correlate subsystems of the universe as collisions, interference, and field fluctuations do. All of them make the universe split and create patterns of organization between physical subsystems. There is no particular kind of interaction that gives us any reason to conclude that there is a collapse of wave functions taking place because there is no sense in which the states of observers and observed systems could be said to single out one determinate subsystem, independently of the rest of

7 The meaning of the *yielding its own interpretation* is then that of giving concrete ways to determine when a measurement has taken place. Some authors (Bell and Torreti among many others) find this notion of self-interpretation puzzling. However, we find that their problem is that they over-read Everett's statement. Everett affirms that relative states are a way to understand, interpret, the fact that the multiplicity of probable outcomes seems to produce a single outcome every time a measurement is undergone. It is by allowing us to clearly differentiate observations (measurements) from other non-registering interactions that the relative state yields its own interpretation. The trick is to understand that "because there exist neither a mechanism between the framework of the formalism nor, by definition, an entity outside the universe that can designate which branch of the grand superposition is the 'real' world, all branches must be regarded as equally real" DeWitt (1971, 392). What Bell (and others) failed to understand is that the self-interpretative nature of the multiple-worlds interpretation is a direct result of the fact that is actually a meta-theory of quantum mechanics: one that permits to point out the moment when, facing experience, quantum mechanical formalism by itself tells us that we are witnessing a world-splitting situation.

the universe's state. This is what the coexistence of multiple worlds is all about, along with its corollary of observers being only able to witness the outcome that makes their own universe possible at all.

The relative state/many-worlds interpretation marks the end of our historical overview of some formulations of the quantum measurement problem and of the way in which alternative interpretations of quantum mechanics deal with it. As we saw, what started as the practical problem of where to draw the line between measuring devices and measured systems became more and more a question about the proper way to interpret the theory from which the problem derives. And it is as an interpretation issue that the quantum measurement problem has become a central question to be addressed and solved by any sound interpretation of quantum mechanics. In the next section, we move to the currently accepted solution to the measurement problem in order to, in the next chapters, introduce some possible alternatives to understand the reach and scope of some contemporary interpretations of quantum mechanics, or better, of some contemporary readings of some classical interpretations, as well as their answers to the so far elusive quantum measurement problem.

1.2 Bell inequalities and the quantum mechanical challenge to locality

From the results of the previous section it might appear that there is no way out of the quantum measurement problem and that we must resign ourselves to the relativism imposed by the alternative interpretations of quantum mechanics. As we saw, the measurement problem is not merely a problem about the formal structure of the theory or the compatibility between its predictions and experimental outcomes. Rather, as J.S. Bell's puts it:

> The continuing dispute about quantum measurement theory is not between people who disagree on the results of simple mathematical manipulations. Nor is it between people with different ideas about the actual practicality of measuring arbitrarily complicated observables. It is between people who view with different degrees of concern or complacency the following fact: so long as the wave packet reduction is an essential component, and so long as we do not know exactly when and how it takes over from Schrödinger's equation, we do not have an exact and unambiguous formulation of our most fundamental theory (Bell, 1975, 98).

The problem at issue then is not about the formalism of the theory as it stands but about the possible interpretations of the formalism. It is in the metaphysical principles that underlie the different interpretations, not in their mostly shared formal structure, that a possible way out of the problem could be found. And it was to make precisely this point that Bell introduced his celebrated argument for the incompatibility between the metaphysical principles of Einstein's realism and the statistical predictions of quantum mechanics.

In a now very famous paper, Bell (Bell, 1964) offered a general demonstration of the statistical relation that holds between the outcomes of measurements of correlated dynamical variables of a composite system at two different spatiotemporal locations. Bell developed a mathematical proof of the fact that measurements of statistically correlated but independent variables[8] taken at two spatiotemporal distant locations depend only upon circumstances in the local vicinity of the point where measurements take place. Stated in probabilistic terms, Bell's argument shows that, for a system whose original configuration exhibits statistical independence, the joint probability for obtaining different results of measurements taken at two distant locations is necessarily the product of the separate probabilities of those outcomes. From this result, Bell concluded that any theory whose description of the interaction between statistically independent systems satisfies this locality condition must necessarily satisfy in turn certain inequalities, the so-called Bell inequalities.

To understand Bell's theorems, let's imagine an EPR-like experiment where two particles 1 and 2 are produced by the same source with a total spin 0 state. Three assumptions have to be added to keep the situation close to the original thought experiment: First, that systems composed of those two particles can in fact be described by a set of hidden variables collectively represented by λ, with classical probability density $\rho(\lambda)$. Second, that the spin components of each particle are measured along different directions, with the convention

8 Statistical independence between two events means that the probability of occurrence of one event does not have any effect on the probability of occurrence of the second event.

added that the value of each measured component is either +1 or –1, and that the result of the measurements of the spin components depend only on the hidden variables λ. What one gets from this assumption is that the results of measurements taken on one particle are independent from the results of the measurements on the other one. In other words, we want our system to satisfy the EPR locality assumption. In order to maintain statistical consistency, we make a third assumption namely, we require that the mean value of the product αβ of the spin components, denoted $P(\mathbf{a}, \mathbf{b}) = \langle\alpha\beta\rangle$[9], which represents the results of a large number of individual measurements, depends on the direction along which the spins are measured.

With the assumptions set, let us denote the average values of α and β as $\langle\alpha(\lambda, a)\rangle$ and $\langle\beta(\lambda, b)\rangle$. By our last assumption, these values depend only on the direction along which the spin component of each particle is measured. We can then write:

$$P(\mathbf{a}, \mathbf{b}) = \int d\lambda\, p(\lambda) \langle\alpha(\lambda, \mathbf{a})\rangle \langle\beta(\lambda, \mathbf{b})\rangle,$$

to represent the expectation value of the product of the two components α and β.[10]

From the fact that α and β can only take the values ±1, (normalizing convention) one obtains the two inequalities

9 α is the component of the particle's 1 spin in the direction a, β the spin component of 2 in the direction b. The additional convention, $\alpha, \beta = \pm 1$ is introduced to simplify the mathematical expressions.

10 We will follow Omnés (1994) presentation of the derivation of Bell's inequalities.

$$|<\alpha(L,a)>| \leq 1, \text{ and } |<\beta(L,b)>| \leq 1.$$

If, using the equation that defines the mean value of $\alpha\beta$, we consider three directions a, b, and c where the vector c is different from b, we obtain, over all the hidden variables:

$$P(\mathbf{a}, \mathbf{b}) - P(\mathbf{a}, \mathbf{c}) = \int d\lambda\, \rho(\lambda)[<\alpha(\lambda, \mathbf{a})><\beta(\lambda, \mathbf{b})> - <\alpha(\lambda, \mathbf{a})><\beta(\lambda, \mathbf{c})>],$$

After a normalization process where a new direction a' is added to generalize the answer, one finds that

$$|P(\mathbf{a}, \mathbf{b}) - P(\mathbf{a}, \mathbf{c})| \leq 2 \pm [P(\mathbf{a'}, \mathbf{c}) + P(\mathbf{a'}, \mathbf{b})].$$

One can see here that in situations where the total spin is zero, the two components, along the same direction, of the spins of both particles are necessarily exactly opposite. Then, $P(\mathbf{a}, \mathbf{a}) = -1$. Replacing this new value in our last inequality, and taking $a' = c$ to represent the spin 0 situation, we arrive to Bell's inequality:

$$|P(\mathbf{a}, \mathbf{b}) - P(\mathbf{a}, \mathbf{c})| \leq 1 + P(\mathbf{b}, \mathbf{c}).$$

What the inequality shows is that there are some restrictions to the possible correlations of measurement outcomes of the spin components of the two particles in different directions. Furthermore, we could conclude with Omnès that the inequality gives a "test for the existence of hidden variables as compared with conventional quantum mechanics, if it turns out that quantum mechanics, which predicts specific values for these correlations P(**a**, **b**), does not satisfy this inequality" (Omnès, 1994, 406).[11]

A noticeable feature of Bell's proof is that it uses physical states to set realistic initial conditions of the statistical situation, i.e., it responds to concrete experimental situations, while the whole argument is developed solely in mathematical terms. This makes the resulting theorems applicable to any theory that uses statistical formalism as its structural core.[12] When the result of Bell's analysis is applied to quantum mechanical systems one finds that, although such systems have the required statistical configuration, they do not satisfy Bell inequalities. Quantum mechanical systems do not obey the "locality condition" that would preclude the exchange of information between distant spatiotemporal ends. We are led then to conclude that:

> In a theory in which parameters are added to quantum mechanics to determine the result of individual measurements [i.e., a complete QM], without changing the statistical predictions, there must be a mechanism whereby the setting of one measuring device can influence the reading of another instrument however remote. Moreover, the signal involved must propagate instantaneously, so that such a theory could not be Lorentz invariant (Bell, 1964).

11 Find, in chapter four, the controvertible case against such a statement. More than a possibility for reinterpreting quantum mechanics in terms of hidden variables, what gets questioned by Bell´s argument is that they (hidden variables) actually represent a local interaction mechanism: locality is at stake.

12 For detailed analysis of the theorems and its interpretations see for example Cushing & McMullin (1985), Bub (1997) and Mittledstaedt (1998).

This is a dramatic result. Any interpretation of quantum mechanics that combines a locality principle with a principle of observer-independent physical systems becomes impossible to defend. Any viable interpretation of quantum mechanics has to choose between the restrictions on faster-than-light information interchange (locality) and the observer independence of quantum systems as its basic interpretative principles. It is possible to have a consistent view of the quantum world from either of these two standpoints, but there is definitively no way in which preserving both locality and independence principles can lead to a result consistent with the predictions of quantum mechanics. The manifest conflict of interpretative principles constitutes the "real" problem with quantum mechanics, a problem that goes beyond any particular interpretation and that highlights the incompatibility of the postulates of quantum mechanics and those of the special theory of relativity (Bell, 1987, 172). What is at issue here is not that the quantum measurement problem changes to the problem of the incompatibility between quantum mechanics and the especial theory of relativity. The measurement problem is actually at the bottom of the incompatibility because, and this is the heart of the matter, both collapse (physical) and (statistical) independence are in Bell's perspective constituents of quantum mechanical systems. What locality proves is the limitation of Einstein's criteria of physical reality, not the definite success of standard quantum mechanics. In this sense, it is because of the failure of its major rival, and not for its own merits, that the standard interpretation's solution to the quantum measurement problem got established as the problem's definite answer. It is precisely because of this situation that, as we are just about to see, trying to solve the incompatibility implies re-interpreting the theory, with all its consequences for a possible re-opening of the issues about measurement.

To demonstrate the extent of the problem, let's see exactly how it undermines Einstein's realistic interpretation. As we saw above, Einstein postulated three requirements for QM to be considered complete: a deterministic account of a system's temporal evolution, realism about physical properties, and compatibility with special relativity, expressed by the impossibility for action at a distance. According to Einstein, quantum mechanics fulfills the first requirement because of its dependence on Schrödinger's (deterministic) equation, while the second and third requirements are in doubt. It is precisely because of the split criteria of physical reality and its implication of 'spooky' at-a-distance influences that Einstein could not second Bohr's optimism about the completeness of the quantum theory. Einstein's solution to the problem rests in his criteria of physical reality; having ever-present physical properties avoids the need for faster than light interaction between distant parts of a system. Given that the formalism of the theory cannot account for those properties, quantum mechanics should be considered incomplete. It might be, perhaps, correct up to certain extent, but definitively needs to be extended to account for the dynamics of the region where quantum systems "become" classical. Besides, only such an extended formalism could help us solve the measurement problem.

According to Bell, the problem with Einstein's interpretation, is that it requires us to believe that quantum mechanics provides a flawless formalism of the physical world at the subatomic level while being totally worthless as a tool for setting up experimental studies of quantum systems. If quantum mechanics has a short view of what is really happening at the quantum level, it is then not just incomplete but certainly wrong. If it could be shown that Einstein's condemnation of the theory rests on suspicious metaphysical principles, then his whole case against it must be reconsidered; just what Bell's inequalities demonstrated with their non locality results. Further experiments may prove or disprove the adequacy of quantum mechanics as it stands, but until those experiments are actually performed there is no reason to reject the theory. As it happened, Aspect's experiments (Aspect *et al.*, 1982) confirmed that particles in EPR-like experiments do not satisfy Bell's inequalities. Combined with Bell's demonstration that any complete description of the quantum world must include non-local principles, the experimental results prove that quantum mechanics contradicts the locality principle on which Einstein's interpretation rests. Thus, Einstein's interpretation of the theory is not a good solution to the problem of the incompatibility between quantum mechanics and special relativity because the incompatibility itself lies at the heart of his interpretation.

But the conflict between quantum mechanics and special relativity is not unique to Einstein's incompleteness interpretation. Bell shows that all current interpretations of quantum mechanics rely on dubious metaphysical assumptions, which he rejects. For example, Bell rejects the Copenhagen interpretation's assumption that the world actually splits at the borderline between the classic and the quantum levels, with physical reality changing from actualities to probabilities. “Quantum phenomena,” states Bell, “do not exclude a uniform description of micro and macro” (Bell, 1987). To declare a division of the world into macro and micro levels introduces an undesirable and inessential metaphysical principle that obscures rather than clarifies our understanding of physical systems.

Furthermore, Bell dislikes Everett’s many-worlds interpretation of quantum mechanics for several reasons. Bell believes Everett’s model misinterprets the role that classical variables actually play in quantum mechanics, and is uneasy with the notion of universes that ‘yield their own interpretation.’ Further, he considers Everett’s multiplication of universes to be an extravagancy: “to have multiplied universes, to realize all possible configurations of particles, would have seemed grotesque” (Bell, 1987, 134). Finally, Bell sees a serious problem with the universe “branching” introduced by the many-worlds interpretation:

> At the microscopic level there is no such asymmetry in time as would be indicated by the existence of branching and non-existence of debranching. Thus the structure of the wave function is not fundamentally tree-like. It does not associate a particular branch at the present time with any particular branch in the past more than with any particular branch in the future. Moreover, it seems reasonable to regard the coalescence of previously different branches, and the resulting interference phenomena, as the characteristic feature of quantum mechanics (Bell, 1987, 135).

According to Bell, the dubious metaphysical conjectures of the many-worlds interpretation rest on the alleged temporal asymmetry of the evolution of physical systems. But such asymmetry, while a fundamental feature of the macroscopic, classical, world, is at odds with the temporal symmetry of the physical laws that govern the quantum realm. Because of this, Bell believes that Everett's many worlds interpretation cannot represent the actual evolution of quantum mechanical systems.

One way to deal with the incompatibility between the interpretative principles is by weakening the statistical independence principle that Bell used as standpoint for his analysis. According to this alternative, it is possible that, even if the experimenters made their best effort to guarantee the independence of the spatiotemporal distant settings of an EPR-like experiment, not every possible influence between distant parts of the experimental settings can be totally eliminated. It is possible that such residual influences are responsible for producing the sort of statistical correlations that are observed when actual measurements are made.

> It may be that it is not permissible to regard the experimental settings *a* and *b* analyzers, [at the distant extremes of the experiment] as independent variables, as we did. We supposed them in particular to be independent of the supplementary variables λ, in that a and b could be changed without changing the probability distribution $\rho(\lambda)$. Now, even if we have arranged that a and b are generated by apparently random radioactive devices, housed in separated boxes and thickly

> shielded, or by Swiss national lottery machines, or by elaborate computer programmes [sic], or by apparently free willed experimental physicists, or by some combination of all of these, we cannot be sure that *a* and *b* are not significantly influenced by the same factors λ that influence A and B [the results of measuring a and b] (Bell, 1984, 154).

Given our current knowledge, the laws governing the evolution of quantum mechanical systems, states Bell, this alternative may not be completely ruled out. However:

> This way of arranging QM correlations would be even more mind boggling than one in which causal chains go faster than light. Apparently separate parts of the world would be deeply and conspiratorially entangled, and our apparent free will would be entangled with them (Bell, 1987, 154).

One can see that the problem troubling Bell is not that the interpretation resulting from modifying the statistical independence assumption is physically unsound. The problem is that this interpretation leads to an incompatibility with some commonsensical principles such as temporal order, causal direction and free will. If measurement outcomes are already determined before measurements take place, then experimenters are not free willed. They may think they are modifying the experimental settings and testing alternative answers to their questions while what they are actually doing is simply acting out roles in a predetermined an already written drama. The behavior of quantum mechanical systems would evidence that a sort of pre-established harmony governs our world, which to our shortsighted eyes seems to evolve locally. The challenge, according to Bell, is not merely one of avoiding the incompatibility between quantum mechanical and special relativistic principles, but to do so without creating a new incompatibility. The new incompatibility that threatens is between the metaphysical consequences of relaxing the statistical independence assumption, and our common sense metaphysical commitments to our free will and the casual and temporal order of physical events.

Bell prefers to embrace the results of his theorems and to use them in a more positive way. The lesson to learn from the current experimental data is that there is in fact a correlation between the spatiotemporal distant ends of certain quantum mechanical systems, as those in EPR-like experiments. When this experimental result is combined with the fact that there is no evidence for the existence of any background ether that could be considered as an absolute reference frame, we are forced by evidence to admit that some causal influences do go faster than light. This is to say that the locality postulate is not only superfluous, but that it conflicts with the experimental results. For this reason, Bell believes that the postulate should be eliminated from any interpretation of quantum mechanics. This approach has the support both of favorable experimental results and of the sound statistical results derived from Bell's work, even if it conflicts with commonsense metaphysical assumptions. With such strong considerations in its favor, Bell's approach became the accepted interpretation of quantum mechanics.

In any case, the strange transition between the quantum micro-world and the classical realm, evidenced by the collapse associated with the measurement problem, remains an obstacle for almost any attempt to move towards an intelligible and definite interpretation of quantum mechanics. That is the content of our next chapter.

9 789587 251821

This book condenses some of the critical features of the discussion about the interpretative problems of quantum mechanics, pointing out some possible ways out of the conundrum. In order to set the road for these matters, chapter one introduces a conceptual history of the theory and its alternative interpretations. Chapter two profiles a taxonomy of the interpretative problems and some possible solutions, focused in the so-called measurement problem. Chapter three questions the thesis of quantum mechanics becoming what it is due to historical contingency. Finally, in chapter four, an argument is advanced to consider one particular interpretation –the causal account- as an alternative view that may help with the solution of the interpretative knot.

UTADEO
UNIVERSIDAD DE BOGOTÁ JORGE TADEO LOZANO

www.utadeo.edu.co