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Epistemological-Philosophical Problems of Quantum Mechanics and Main Solution Attempts: An Overview

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Abstract: This work presents a historical-epistemological analysis of the foundations of quantum mechanics. From a philosophical point of view, the relationships between quantum mechanics and scientific realism are highlighted, as well as the influence of the neo-positivist philosophy of the first decades of the 20th century. The great significance of measurement in the context of quantum mechanics is underlined, as an essential element in providing a coherent description of reality moving from the microcosm to the macrocosm, as well as the role that the measurement apparatus and the consciousness of the observer assume during the act of measurement, the ontological problem, the problem of the objectification of the wave function and the problem of the definition of discernibility. This is followed by an overview of the most important alternative proposals to the standard interpretation (Copenhagen interpretation), with particular reference to hidden variable theories, and other alternatives to standard quantum mechanics that profoundly modify the vision of reality, such as the Everett's many-worlds theory, the QBism, the unified holistic approach.

Keywords: philosophy of science; quantum mechanics; foundations; open problems; ontology; epistemology; hidden variable theories; alternatives to standard quantum mechanics; holistic unification

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1. Introduction

The twentieth century was characterized in particular by the advent of quantum theory. After almost 300 years of classical physics, the microscopic world brought to light a series of results in sharp disagreement with Newtonian mechanics. Even today, there are many difficulties in explaining the profound meaning of quantum mechanics; the physical meaning of this theory has been not yet fully understood, although many applications of the theory are leading to surprising improvements at a technological level.

The undisputed success of the mathematical formalism that supports quantum theory led to two very different ways of approaching the problem of "how to do science": on the one hand, resorting to intuition and referring to tested conceptual schemes, on the other to be guided exclusively by formal developments, without worrying about their intuitiveness.

Regarding the interpretative problems of quantum theory, extreme importance concerns the "measurement problem", which in quantum mechanics is not trivial at all, especially if one embraces the orthodox vision of the theory, known also as the "Copenhagen Interpretation". The act of measurement involves a disturbance, which makes complex to attribute properties to the object independently by the experimenter, therefore being able to separate the object to be investigated from the measurement apparatus and the observer. In the orthodox version of quantum reality, the experimenter contributes to determine the answer and has an important role in creating the answer.

Following this interpretation, the hope of restoring the sense of an underlying physical reality must be abandoned, as it is considered "metaphysics" devoid of scientific meaning in the strict sense;

physics at this scale seems to have reached the terminal point, without the possibility of acquiring deeper knowledge and leading the world of physics to a division between realist and anti-realist philosophies.

For this reason, the main creators of quantum mechanics developed, in addition to the theory, a series of *ad hoc* postulates to express the mathematical predictions of the equations in evident and observable properties such as, for example, the determination of the position of an electron in a given instant, the process by which an electron instantly passes from a state of "everywhere" (quantum microscopic world) to one of "here or there" when observed (macroscopic world).

This is a questionable view, but it has been accepted as orthodox; over the years, alternative interpretations have been developed that solve the measurement problem, such as the de Broglie-Bohm hidden variable theory, the Everett many-worlds theory and the GRW theory of spontaneous collapse.

Another big problem concerns the predictive success of the formalism, which however is insufficient in convincingly describing the reality around us, leaving the task of addressing these problems to philosophy, and not to science. Therefore, the standard vision of quantum mechanics does not provide a realist description of what surrounds us, not allowing to describe the reality independently of the act of observation; it has oriented science towards one of two directions: giving a too decisive role to the observer or saving the phenomena.

Another fundamental problem concerns the understanding of the connection between body and consciousness, what makes an object conscious, whether consciousness concerns only or also the things that surround us. Various answers have been given to this question, the main ones being:

a) Consciousness could be caused by complexity. A sufficiently large system, with degrees of freedom and interconnections between its parts, could be conscious, have a certain degree of consciousness, and this in less complex systems than the human brain, and theoretically in other more developed ones.

b) It could be something new, beyond known physics, such as a holistic theory based on a primordial space with peculiar properties. This would lead to a consciousness of the whole; particles and objects could choose how to behave, and be influenced by our thoughts. This is a truth that cannot be adequately expressed in the terms we know and are using do date.

We can summarize the great ontological problem of quantum mechanics in these terms: in the used formalism the fundamental element is the wave function ψ with which we describe the physical state of a microscopic system, but it is not clear how it can be understood as a description of material structures in our three-dimensional physical space.

Wave functions are not able to explain every result that we observe in measurements of the three-dimensional physical reality, also considering that they are defined in an abstract and multi-dimensional configuration space, with a dimension greater than three.

Another big problem is that of distinguishability. In the common sense, two objects A and B are considered different if the first possesses/does not possess some characteristic or property that the second does not possess/possess. The way in which the human being, already as a child, classifies the objects, i.e. through the attribution of names, enters into crisis during his development when he realizes that there are objects that change without passing through discrete intermediate states, but in a continuous way.

For example, an ice cube exposed to the sun melts and is called water; what was previously classified on the basis of intrinsic properties, i.e. monadic properties of the object, therefore not including the object's relationships with other objects (i.e. extrinsic properties), is called differently. This leads to the question: is the object still the same or is it something different? Is it correct to make a distinction between ice and water?

There are physical objects that have a clear definition (such as a house, an animal), non-physical objects that can be defined in clear terms (such a bank account, a tax code) and non-physical objects whose definition is ideal, but which have very important implications in the physical field (such as the concepts of space and time).

A human being, throughout his physical and mental development, can affirm that an object, physical or otherwise, is a construction made by his own mind on the nature that surrounds him and which he has experienced [1,2]; the question of whether he can identify a physical object only on the basis of its intrinsic properties, such as mass, charge, and its space-time properties, is not yet fully clarified.

A quantum object, such as an electron, cannot be investigated directly but through the consequences of its behavior within a given experiment; some elementary particles are also considered to have no mass (neutrinos and photons). We are therefore not able to continuously follow a quantum object over time; this leads to considering it as a "non-material object" or in any case in need of further philosophical reflections.

Elementary particles are not so strange in everyday life; they compose macroscopic objects according to the results of the latest scientific theories, in particular statistical mechanics. The search for a broader general definition of object, including also microscopic objects, is therefore considered necessary.

The following paragraphs summarize the principles of quantum mechanics and the related structure of science (§ 2), the main attempts for solving the problems presented by standard quantum mechanics (§ 3), the epistemological-philosophical issues related to quantum mechanics (§ 4) and the conclusions (§ 5).

2. The principles of Quantum Mechanics and the Structure of Science within Quantum Physics

Quantum (non-relativistic) mechanics is one of the pillars of modern physics together with the theory of relativity; it is based on precise principles formalized in mathematical terms:

a) Superposition principle: given two states of a system, any complex linear combination of them is still a state of the system. In classical mechanics this is not always true.

b) Uncertainty principle: it is not possible to determine the value of a physical quantity at a specific instant; one can only provide a probability distribution.

c) For each physical observable associated with a system, there corresponds one and only one self-adjoint operator in the Hilbert space.

d) The possible values that a physical quantity can take on following a measurement process are all and only the points of the spectrum of the respective self-adjoint operator.

e) Every vector in the Hilbert space is an eigenstate of a suitable operator, and the operators do not necessarily represent physical observables.

f) The temporal evolution of a system is obtained from the solution of the time-dependent Schrödinger equation with appropriate initial conditions.

The mathematical theory on which the foundations of quantum mechanics are based is the theory of linear operators in Hilbert spaces, in particular the theory of self-adjoint linear operators and their spectral analysis [3,4].

Quantum mechanics has established above all for its notable predictive success and for the vastness of the applications it has made possible, despite being born with philosophical foundations full of profound contradictions. At a microscopic level, there is a sort of unknowability of nature and, despite multiple attempts made to date, it does not seem possible to find a theory that has a greater explanatory power than it, at least at the level of applications with a direct effect on objects we use in everyday life. It seems to violate the principle of causality, on which classical physics and rational thought in general are based, including the theories of special and general relativity.

One of the experiments that led to the birth of quantum physics was the double-slit experiment which revealed the problem of the nature of the different behaviors of light. This experiment marked a profound break with the tradition of classical physics, highlighting the fall of the distinction between matter and radiation; particles are in fact classically localized entities while waves are diffuse entities.

This is a problem of extreme importance, which led to the hypothesis of a co-presence between these two natures, then further refined with various hypotheses, including that of the pilot wave, which would drag the corpuscle.

In classical physics it had never been found that the measure of the behavior of a particle modifies the interference phenomenon and that energy is transferred discontinuously; this led to Planck's quantum of action and subsequently to Einstein's light quantum hypothesis, according to which radiation is composed of corpuscles [5].

Science tends to be based on an interactionist view of discovery; physical phenomena involve an interaction between what is observed and the observer who experiences. When dimensions become very small, uncontrollable interactions can occur and the nature cannot be observed in its totality. Therefore, measurement takes a decisive role in quantum mechanics; it is an interaction with a mutually exclusive character between conjugated quantities, which define completely the system.

Among the possible historically advanced solutions there is the possibility of something extra-physical that violates the quantum superposition, determining a finite measured value, such as the consciousness of the experimenter, or it is necessary to completely reformulate the theory to eliminate the a-causality [6]. In fact, quantum mechanics claims that before a particle is randomly localized, it is in a certain sense present everywhere, disappearing from everything else at the moment of localization. It also violates the cause-effect principle, involving retro-causation phenomena [7].

Delayed-choice experiments highlight the complementarity between wave and corpuscular behavior of particles and show that if the observer interacts with the system, he can change the past of the system with a choice in the future, resulting in a modification of the universe itself with his choice; the universe does not exist except in the presence of the experimenter who in a certain sense creates it [8]. The retro-causation, shown by delayed-choice experiments, is an interpretative possibility; these experiments reveal the impossibility of interpreting the empirical evidence on conceptual bases linked to common sense.

3. Attempts to Resolve the Presented Problems

3.1. Hidden Variable Theories

This type of theories is characterized by the explicit presence of elements not present in the orthodox formulation, through the addition of further variables to the quantum state vector which appear directly in the measurement results. By introducing these new variables, it is possible to give a clearer explanation of the experiments. These theories could restore a realist vision of nature. The best-known hidden variable theory is the "de Broglie-Bohm theory" [9].

These theories foresee to assign a precise value to any observable, determined by the hidden variables; therefore, in particular, the position on the observable apparatus will always have a well-defined value, depending on the value of the hidden variables that characterize it. They constitute a completion of quantum mechanics in a deterministic sense, everything depending on the entire context and therefore not univocally on the variables.

In the non-relativistic context, the interpretative problems of orthodoxy from its foundations, i.e. from the Schrödinger equation, are highlighted. Attempts of extension to a relativistic context lead to even more complex interpretative difficulties.

3.2. The de Broglie-Bohm Theory

The theory was first proposed by de Broglie and later developed independently by David Bohm; it is also called "Bohmian mechanics" and "pilot wave theory". This theory does not predict that particles are wave-like when not observed, then collapsing into precise positions following a measurement. The particle has always a very precise position, which follows defined trajectories in space; statistical wave phenomena arise because the motion of the particle is influenced by a wave associated with it [10–12].

A single electron is a wave and a point-like particle, whose motion is controlled by the wave. Each particle is always defined somewhere, but in carrying out an experiment it is not possible to choose which position value is actually realized within the distribution; nature chooses which initial position the particle has. This hypothesis preserves the fundamentally random character of the predictions of quantum mechanics, with the big difference that nature chooses the initial position of the particle; it is not as in the orthodox interpretation, where the particle does not have a defined initial position before the measurement.

The added variable depends on the wave function for its initial value and its evolution; the positions are dragged by the wave function and can never move away from it. One can then restore determinism and assume that the measurement results reveal the pre-existing value of the positions, chosen from all possible values in the initial probability distribution [13].

This hypothesis resolves various difficulties, for example those related to understanding the quantum manifestation of both wave and corpuscular properties in interference experiments. Containing the system two inseparable entities, a wave and a particle, the wave can produce interference effects and guide the particle in such a way that its trajectory reproduces the interference pattern, resolving an aspect that is no longer mysterious from a conceptual viewpoint. The "wave-particle dualism" is on fact a dualism, but it is not an enigmatic dualism as in the Copenhagen orthodoxy.

The extension of the theory to the case of many particles is formally simple, and manifests its non-local character, solving the ontological problem [14]. Pilot wave functions live in the three-dimensional space, and effective potentials imply instantaneous interactions at a distance; the theory correctly reproduces the statistical predictions of ordinary quantum mechanics.

Each particle passes through only one slit, but the wave function evolves differently when both slits are open compared to when only one is open, and this consequently influences the motion of the particles. With this theory it is not necessary to divide the world into classical and quantum in order to understand the measurements and their results; it is possible to treat the system and the measuring apparatus in the same way.

The theory generates the same statistical predictions of ordinary quantum mechanics, even though it is completely deterministic; the wave function follows the Schrödinger equation, which is deterministic, and the randomness is given by the initial conditions. We cannot know in advance the result of a quantum measurement, since we cannot know exactly the initial positions of all particles of the system, being these the hidden variables of the model.

3.3. Further Elaboration of the Bohm Model

A further elaboration of the Bohm model is known as the "Bohm-Bub model"; it has the advantage of describing quantum physics using additional variables and provides a deterministic description without the introduction of an arbitrary system-apparatus separation, representing an advance towards the creation of a more complete and coherent quantum theory than the standard one [15–17].

3.4. Statistical Interpretation

Over the years, other alternatives to the standard interpretation have been created, which also move away from a realist vision, while still proposing a solution to the problem of measurement. This type of model does not eliminate the possibility of describing individual physical systems, but specifies that the description given by a state vector can only be applied to a set of systems prepared under the same conditions, not to individual systems or individual experiments.

The ψ function contains information similar to that of a distribution in the phase space of classical statistical physics, which *de facto* is not the most exact description of a physical system; it is only a mathematical tool representing statistical information that allows the calculation of the probabilities that certain phenomena occur [18].

Within this type of interpretation, two orientations are possible from a logical point of view:

a) Not being able to describe individual systems, the theory is not complete, but further variables must be specified for identify the individual system within the whole; this leads to the introduction of new descriptive elements in addition to the state vector, i.e. to the introduction of additional variables.

As in the case of classical statistical mechanics, this type of interpretation assumes that each system has well-defined properties before the measurement and that the measurement shows

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something pre-existing, not implying that it is possible to predict or control these properties [19]. In these terms, the probabilities in quantum mechanics are not different from the classical ones; they reflect our ignorance, just as the quantum state shows our incomplete knowledge of the physical system.

b) The statistical interpretation does not inform about what happens to individual observed electrons, but only talks about distributions of measurement results over a collection of similar experiments; furthermore, it does not provide a clear distinction between individual macroscopic and microscopic objects, as it does not have a description of the latter and the existence of individual physical systems in nature is an indisputable fact [20]. A possibility is that this statistical interpretation is the first step towards a theory that describes the behavior of individual systems; it would necessarily be a hidden variable theory.

3.5. The Relational Interpretation

The relational interpretation ignores the notion of absolute state, independent of the observer, of a physical system; different observers may give different reports of events, using different state vectors. The difference does not derive from the use of different reference systems, but from different information available to observers, from the use of different measurement devices. The physical properties of systems are therefore seen as dependent on the apparatus used to measure them, considering quantum mechanics as an "information theory" [21].

According to this interpretation, the collapse of the wave function assumes a different role from what it represents in the orthodox interpretation; for a given quantum system, some observers might consider the collapse as already occurred, while for others it has not yet occurred, being the system still in a coherent superposition.

The centrality of the role of measuring devices and of the observers in the standard interpretation is not essential in the relational interpretation; the observer does not make any special reference to a conscious and animate system, but the term information is used in this context in a much more physical sense, which can also be manifested in inanimate objects.

The existence of an objective reality, independent of any observer, existing even when no one is looking at it, is not denied, but it is not possible to discover anything about it. It becomes meaningful to talk about quantum states and properties of such reality only when it establishes a relationship with another system, a position that does not question realism, but scientific realism.

According to this interpretation, quantum mechanics is only concerned with relations between things, not with the actual properties of physical things independent of the relation; the mathematical relations used in quantum mechanics do not refer to the independent physical states of quantum systems, but to the information on the quantum system resulting from our experience. The measurement process is considered a physical interaction like any other, without a special role within the theory.

3.6. Quantum Bayesianism

A line of research has taken an extreme information point of view, where the wave function ψ is totally disconnected from physical reality, considering only the information content of the state vector. This interpretation is called "quantum Bayesianism" (briefly QBism), is one of the most recent interpretations of quantum mechanics and strongly linked to quantum information.

The subjective Bayesian view of probabilities considers them as simple judgments; probabilities essentially reflect our degree of knowledge of the world, therefore different people assign different probabilities to the same event, and this applies even to the most complicated situations [22].

QBism extends this subjective view to quantum probabilities, giving to quantum states a purely subjective meaning. It can therefore be considered a return to the Copenhagen interpretation, but in a much more consistent way, since for the standard interpretation the quantum state of a physical system identifies objective properties following the system-apparatus interaction, and not judgments [23].

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According to QBism, there is no true quantum state, there are only degrees of coded information that deviate from the perspective of something "outside" the observer and can instantaneously change. It is a vision that concerns only subjective experiences, not the external world, even macroscopic, is a radical idealism. QBism assumes, in a certain way, a local vision, but also a solipsist one, it is a "single user" interpretation, with experiences and degrees of belief unique to the individual.

The subjective nature of individual experiences entails that each person has in his mind "different versions of reality", shaped by personal experiences on what should be a single external empirical reality, with respect to which he interacts. The great similarity of these individual backgrounds makes human interaction possible, and everyone perceives these separate realities as only one.

QBism is therefore a position that can be classified as anti-realist; all physics beyond our experience is in principle inaccessible. This point of view can also be applied to classical mechanics [24,25].

3.7. The Theory of Spontaneous Collapse (GRW Theory)

The central idea of spontaneous collapse dates back to the Bohm-Bub theory, in which the hidden variables are a kind of background field, which influences the evolution of the wave function by deviating the canonical evolution described from the Schrödinger equation. This prompted to explore the possibility of possible stochastic modifications to the Schrödinger equation.

If it is possible to obtain the exact positions of macroscopic objects, other properties can reasonably be obtained as well, since the results of measurements of other properties (energy, momentum, spin, etc...) are always recorded by the position of some macroscopic object. The theory of spontaneous collapse took shape from considerations of this type, which is based on the idea that wave functions must occasionally randomly localize in an exact position [26,27].

According to this model, at randomly selected times, through a position measurement by an external observer, the particle's wave function would collapse into a Gaussian wave packet, rather than a delta, thus avoiding the problem of the external observer. Occasional collapses of the wave function are to be considered natural, in the ordinary way in which wave functions evolve over time; the wave function evolves according to the Schrödinger equation, except for these moments when it undergoes spontaneous localization.

This is an interpretation that is not totally different from the orthodox interpretation, but, unlike the latter, it is not necessary to introduce an *ad hoc* hypothesis such as that of the collapse of the wave function. This interpretation resolves two important problems of measurement theory: the collapse of the wave function and the distinction between microscopic and macroscopic systems, aspects that are quite problematic in the standard interpretation.

3.8. The Many-Worlds Theory

The standard formalism requires two incompatible dynamical principles (the linear Schrödinger equation and the wave packet reduction) and is unable to specify when to apply one or the other. An attempt to resolve this situation led to the development of the many-worlds theory; in it the reduction process is eliminated from the formalism, generalizing the validity of the Schrödinger equation and including the observer himself in the physical description [28].

The observer is considered as an external spectator to the process and there is his radical involvement; not being able to avoid the laws that govern all events, the only reality is represented by a wave function containing all possibilities, including those of observers with incompatible perceptions, which is essentially the meaning of entanglement.

It is an orderly combination of several manifestly reasonable individual situations; successive interactions bring more and more "reality" into the ever-overlapping combination, describing all these possibilities that evolve in parallel. All the various parts of the wave function correspond to macroscopically and cognitively incompatible situations, therefore they must refer to different worlds, among which there is no relationship.

All possible results included in the state actually occur, but in a multiplicity of worlds that do not communicate with each other; no reduction process occurs, and the Schrödinger equation governs the entire physical process. By eliminating the hypothesis of the collapse of the wave function, the model solves the measurement problem in a simple way [29].

3.9. The Multiverse: Deutsch's Interpretation

The many-worlds theory has been reworked in relation to the notion of "multiverse" [30]. Assuming that electrons maintain integrity as real and localized particles, it is possible to interpret the two-slit experiment by considering each electron accompanied by "ghost electrons" that pass through both slits and interfere with the path of the visible electron.

They would therefore influence the path of the visible electron, but are not detectable; an explanation for their existence lies in considering them not existing in our universe, but in parallel universes, similar to our "visible" universe; each such universe would obey the same laws of physics, but differing in the fact that the particles are in different locations in different universes. The interference between particles in our universe is therefore not a quantum wave interfering with itself, but particles in parallel universes interfering with a particle in our tangible universe [31].

This reinterpretation does not limit to saving the phenomena, but supports the idea that an adequate physical theory should describe and explain what we see in our reality; it is therefore critical versus the Copenhagen orthodoxy, which denies realist and explanatory approaches. It should be underlined, however, that what is meant in this case by "quantum reality" is different from the assumptions considered by the defenders of realist approaches to quantum mechanics, i.e. with the fundamental requirement of remaining substantially in contact with experiential reality, a requirement not satisfied by the multiverse [32].

3.10. The Many-Minds Interpretation

This interpretation can also be considered a modified version of the many-worlds theory, in an attempt to overcome some of its criticisms. The basic idea concerns to consider, instead of an infinity of worlds (an infinity of copies of each conscious observer), a single world and the observers endowed with an infinity of minds, each of which selects one of the different outcomes of each process with perceptually different outcomes [33].

In the many-worlds interpretation all possible events are given, whereas in the many-minds interpretation all possible perceptions are given. In order to guarantee the interpersonal agreement, it is accepted that people's minds are in some way "synchronized", such that if two or more people participate in the same physical process associated with different cognitive states, such as for example the overlap of state "sound emitted by a device" and "sound not emitted", the mind of the person who conscientises the perception of the sound must be synchronized, i.e. in the same term of superposition, with that of others.

4. Epistemological-Philosophical Questions

4.1. Determinism, Contextuality, Realism, Ontology

Standard quantum mechanics is a non-deterministic theory at the ontological level. In the de Broglie-Bohm theory the precise trajectories are defined at any time, but are empirically unknown, since the initial positions are hidden variables; it is therefore not capable of producing deterministic predictions, like the standard formulation. This model is therefore deterministic at an ontological level, but is probabilistic with respect to the possible predictions of quantum measurements [10,11,34].

The probabilities are epistemic, i.e. linked to the limits of the observer's empirical knowledge of the quantum system, rather than ontological, i.e. related to the intrinsic characteristics of the model. Therefore, in Bohmian theory quantum probabilities do not have a profoundly different character from classical probabilities, and this would solve the problem of objectification.

For every quantum system there exists at least a complete set of compatible non-contextual variables, i.e. which allow the results obtained by Bell, Kochen and Specker not to be violated. They are the variables that can be measured objectively, independently of all other measurements performed on the system. In Bohmian theory, positional variables are the only non-contextual variables in the theory [35,36].

The de Broglie-Bohm theory is therefore to be considered a realistic model, provided that the measured quantities are only positional ones. All other variables are contextual, and therefore unrealistic, also defined as "almost real".

Trying to give a clear physical meaning to the wave function is a very problematic issue, since it is not obvious how it can describe the events that happen in physical space. The theory of spontaneous collapse would solve the problem, since it, using the Everett's point of view, would allow only one branch to survive.

Everett's branches do not communicate with each other, so this overlap would only be observed by a possible "observing God" external to the individual branches; human observers in a single branch do not perceive the existence of the other branches, therefore for them the situation is clear and they observe a coherent macroscopic situation.

The hypothesis of incommunicability between the different branches of the universe has been criticized by some supporters of the orthodox vision, even if in fact this can be understood by introducing decoherence within the theory; many degrees of freedom are involved in a measurement process, therefore at a macroscopic level the branches are not interacting with each other [37].

4.2. On the Problem of Individuality

Assuming to have an adequate definition of "object", the question of its individuality becomes a fundamental issue for managing objects. One of the most widespread conceptions of individuality is focused on the space-time properties of physical objects, together with the property of impenetrability and permanence along space-time paths, but even all this does not seem to be enough [38].

In the attempt to establish in the best possible way the individuality of a physical object and distinguish it from other objects, two main tools are commonly used, which are not alternative, but distinct: the mereology and the search for a principle of individuality.

Mereology is a philosophical discipline that studies the relationships between the whole and its parts, focusing its questions on composition through questions such as: Can a whole object be completely determined by the sum of the elements that constitute it? Is the whole more than the sum of its parts? What is meant by parts of a whole object? [39,40].

From the birth of the universe up to the present day, considering valid the Big Bang theory, and in particular at beginning, every particle has interacted with other particles, logically implying that the universe in its totality is considered a whole that cannot be separated into parts (objects) independent of each other. This is a strongly holistic position, connected to an anti-reductionist thesis according to which quantum mechanics contains an "ineliminable holism", whereby the whole is more than the sum of the component parts [41]. The whole would therefore manifest emergent properties and this comes into conflict with the metaphysical doctrine of reductionism, which is manifestly the implicit position in scientific practice [40,42].

The second way to understand the individuality of an object is to search for an effective principle of individuality and identity that is resistant to the changes that take place in the field of science.

4.3. On the Problem of Separability

The problem of non-separability calls into question not only field theories such as Einstein's relativity but also every physical theory, as it is, according to Einstein, a necessary condition from a theoretical point of view.

Non-separability in quantum mechanics can be defined as the property according to which the quantum states of two physical systems are mutually dependent; modifications in the state of the first physical system lead to instantaneous alterations in the second system, regardless of their spatial location [30,43].

Microscopic objects are not the same as those of classical physics, they are objects that must be interpreted in a new way. It has been also suggested that they are mathematical objects, such as the wave function that describes the state of a physical system [44].

One of the solutions that has been among the most acceptable to date is the one that emerges from Bohr's principle of complementarity: for the understanding of the physics of microscopic objects, and for the representation of the phenomenon, there is a need for images linked to classical physics, although this image is contradictory, considering the wave-particle dualism; in experiments, such as the double-slit experiment, the two aspects coexist, but not fully [45]. This indicates the subjectivist aspects of the theory, because in the attempt to establish the path of the particle, an apparatus is introduced that disturbs the behavior of the particle.

4.4. On the Mind-Body Problem

Quantum mechanics rekindles a distant problem of the metaphysical tradition, the mind-body problem linked to the philosophy of mind; the transition from an overlapping to a non-overlapping situation is *de facto* linked to a change in the experimenter's knowledge.

Every knowledge of the experimenter is connected to a mathematical description, which however does not seem to be able to grasp the totality of physical reality, which is richer than the mathematical representation; every mathematical object has a counterpart in physical theory but not vice versa. However, the mathematical representation is richer than the experimenter's information [46,47].

If the current quantum description of reality were complete, we would be faced with two possibilities of choice:

- a para-psychological description is accepted that mental states produce changes in physical reality without having a material support [48,49];

- quantum mechanics describes only the observer's knowledge of reality and not reality; in this case it is a psychological solution, which no longer has any relationship with reality and is therefore anti-realist [50].

4.5. On the Problem of Locality

In an attempt to make the conservation of energy and momentum coexist with probabilistic interpretation, Einstein introduced ghost fields that satisfied "quantum randomness" and supported the explanation of wave interference phenomena [51]. Schrödinger solved the problem by moving the domain of applicability of wave functions from the physical space to the mathematical space of configurations, at the cost of non-separability.

The ontology required by Einstein is an ontology of separable states, in which every point in space is identified by a metric tensor, and with the conservation of energy and momentum, as required by a field theory. This is not true in quantum mechanics: either there is conservation of energy and momentum or there is localization of the system [52].

If we therefore accept the completeness of quantum theory, we come into conflict with the theory of relativity, because the postulate of reduction and localization is a process that occurs instantaneously and is therefore incompatible with the theory of relativity.

Locality and separability are fundamental principles based on the ontology of field theories; the realism of the regions of space-time is represented by the metric tensor and the interactions are described by the changes of real and distinct states. The ontology is therefore that of a space-time manifold with metric tensors and with structures related to energy and momentum. Einstein had strong methodological, epistemological, and metaphysical arguments for maintaining both locality and separability, which explains his constant commitment to maintaining a field theory as an alternative to quantum mechanics.

The double-slit diffraction experiment is totally incompatible with the corpuscular hypothesis, as the classical nature of quantum particles (independence and localizability) has no explanatory power regarding the interference structure obtained in the experiment [53].

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Schrödinger's wave mechanics had brought a new element into quantum theory, namely the concept of non-separability; this concept, both from a physical and epistemological point of view, was not acceptable according to Einstein, as separability is a necessary condition for having determinism. This position was also endorsed by Bohr: the desire to derive the equation of motion of the particle starting from the parameters of field theory leads to separability between particles [54,55].

Einstein expressly believed that to have a correct and complete scientific theory it is necessary for it to be a field theory, and if this is the case then both locality and separability certainly apply to it. The latter properties appear to be violated by quantum mechanics, and therefore this theory was considered incomplete [51].

Einstein, Podolski and Rosen assumed the following conditions in relation to the formulation of the famous paradox (EPR paradox):

1) Reality Principle, formulated as a sufficient condition of physical reality in the following terms: if, without disturbing a system in any way, it is possible to predict with certainty, i.e. with probability equal to 1, the value of a physical quantity, then there is an element of physical reality corresponding to this physical quantity. Einstein considered this principle sufficient, considering necessary the condition of completeness that "every element of physical reality must have a counterpart in physical theory" (property defined as objective) [52].

2) Locality: considered a physical system isolated from the system under examination, no operation conducted on it can modify the objective properties of the system under examination.

3) Completeness: the physical theory that describes the system under examination captures all its objective properties.

4) Anti-correlation: the spin measurements in two subsystems constituting the system under examination are always opposite [56].

All this did not create problems with the "arrow of time", however questioned with the Wheeler's delayed-choice mechanism of the future on the past. There is indeed a nomological reversibility of all fundamental laws of physics and irreversibility emerges as property at the level of macroscopic thermodynamic phenomena. The act of measuring and recording of quantum mechanics is also irreversible, while quantum mechanics is reversible [57,58].

With the used reality criterion, Einstein, Podolski and Rosen moved the notion of reality from the object to its predictable properties; in metaphysical realism reality goes beyond science itself, it is something additional, while in the conception of Einstein, Podolski and Rosen it shifts to properties predictable through scientific theories.

The paradox was explained with the retro-causation hypothesis, considering a distinction between "macro special relativity" and "micro special relativity"; micro special relativity would not have the arrow of time and therefore retro-causation would be possible, an action therefore prohibited only by macroscopic physics but not by microscopic one [59]. This solution is admissible from the point of view of mathematical formalism but contrary to reductionist philosophy, and would call into question space-time contiguity and causality, moving the problem from the EPR paradox to that of measurement. Even the construction of hidden variable models that renounce to the space-time contiguity would allow quantum theory to come closer to a special reality [60].

4.6. On the Problem of Measurement

A solution to the measurement problem, which however clashes with entanglement, was given by Hugh Everett and is acceptable from the point of view of mathematical formalism. The idea concerns a multiple evolution; the observed states evolve in a deterministic but not objectivist way, the system assumes a given state following a measurement, and in addition all the possible states are in other universes, perfectly identical but not communicating with that of the observer [28]. However, this is an idea contrary to the reductionist philosophy of Occam's razor, because it increases the involved entities [61,62].

Important issues that the 20th century neo-empirist philosophical tradition had deemed not to be of considerable importance, such as the mind-body problem, the problem of realism, the problem

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of causality, the problem of holism, the problem of being and nothingness, have become fundamental issues of considerable physical interest.

Among the various attempts to explain the reduction of the wave function, the von Neumann's interpretation considers the consciousness of the observer as the element that carries out the reduction [63], the Bohr's interpretation is based on the measurement apparatus as responsible for the collapse of the wave function [54], another explanation considers the reduction of the wave function as occurring spontaneously and indicated as an evolution towards equilibrium [64]. Interactionist and mentalistic explanations have also been given [45,65].

4.7. Empirical Realism in Quantum Mechanics and the Structure of the Vacuum

The understanding that the vacuum, i.e. nothingness, has physical, not just metaphysical properties, is increasingly evident; it is not a question of the total absence of the determination of being, but of the possible absence of particles, in the ordinary sense of the term (non virtual particles). Giving meaning to nothingness is a possible and promising solution compared to those that undermine the traditional points of view on the mind-body problem, namely:

- the materialist ontology, which slows down the progress with the philosophy of mind;
- the psycho-physical panism, according to which physical events influence each other;
- the epi-phenomenism, according to which events are dependent and there can be physical and psychological influences that act on mental states.

In this regard, recent studies in progress on the structure of the vacuum attempt to present also in a technical way a "primordial dynamic space", endowed with peculiar properties, which can be used as the basis for a unified holistic theory, and from which it would emerge the ordinary space-time with the surrounding reality, following phenomena of emergence and decoherence [40,42,49,66].

Science appears to be the best area in which to found the realist conception, but quantum mechanics put this position into crisis, together with other philosophical assumptions including that of the identity of indiscernibles. A way of addressing the issue is therefore to understand which philosophical presuppositions and which assumptions need to be reformulated or eliminated.

4.8. On Quantum Logics and Quantum Statistics

The foundations of quantum mechanics led some scientists and philosophers to seek an explanation through a transformation of the fundamental laws of logic; the double-slit experiment has been interpreted as an example of a physical situation that leads to the abandonment of the laws of classical logic. A non-classical logic has been developed, more suitable for describing physical phenomena linked to quantum mechanics, affirming the invalidity of certain properties [2,67–70].

It has been shown the possibility of correctly describing the double-slit experiment or experiments such as Wheeler's delayed choice experiments, maintaining the Boolean algebra and thus not violating the distributive property; these are formal solutions to a physical problem which however do not help to understand the situation, i.e. explain the nature of the superposition but not the problem of measurement.

Unobserved systems follow the quantum logic; as soon as a measurement is carried out, classical logic is followed because the interference is destroyed [71,72]. We therefore return to a strongly subjectivist character of quantum theory. Another path is to consider the additivity of probabilities in quantum mechanics to be illegitimate [73].

Other attempts concern "quasi-set theories", which allow the vision of the quantum world of indiscernible particles to be logically adjusted and in which the classical concept of set and the principle of identity of indiscernibles are put to the test [74] .

Statistical mechanics was born as a scientific discipline with the aim of deducing macroscopic laws starting from microscopic ones; the models analyzed in statistical mechanics are probabilistic models that presuppose a probability measure. The best known and most used statistics are classical (Maxwell-Boltzman) and quantum statistics (Bose-Einstein and Fermi-Dirac) ones [75].

It is possible to trace the beginning of quantum statistics through the works of Planck [76,77], who provided hypotheses on quantum mechanics, Gibbs [78] and Einstein [79], who laid the foundations of chaotic motion later called "Brownian motion".

Quantum statistics has achieved considerable success over time and has established itself in particular for its anticipatory capabilities of quantum phenomena; its success is linked to a new formulation of the foundations of statistics, which allowed the justification of experimental evidence in the quantum ambit. Its first successes were the calculation of the energy density per unit volume of the electromagnetic radiation spectrum and the understanding of the wave-particle duality of light.

5. Conclusions

The meaning of the wave function is a complex combination of different concepts regarding reality and the knowledge of reality that human beings have. Standard quantum theory has undoubtedly had great results and applications over the years, but this is not sufficient to assert that provides the definitive description of a quantum system; even its compatibility with realism or the demand for a positivist position are not resolved questions.

The wave function is an extremely useful tool, but the concept of reality cannot be comprehensively defined at its level alone. The problem generally concerns the degree of prediction of a physical theory, i.e. whether it is sufficient for it to make correct predictions, without contradiction with experimental results, or it is essential that it tries to correctly describe and interpret real events.

Not all physicists and scientists agree on the answer to questions of this type. However, these are legitimate questions, which inevitably require reflections of a philosophical and epistemological nature, as well as strictly scientific nature.

The development of a fundamental theory, capable to convincingly describe the passage from the micro-world to the macro-world, the problem of measurement, and the resolution of problems such as non-locality and determinism, require responses not only from theoretical physics, but also of a philosophical and theosophical nature, such as holistic theories.

The schism between realists and anti-realists remains in science, and the philosophical in-depth analysis can help in resolving it; the exclusion from scientific reasoning of arguments defined as "metaphysical" risks the drying up and stasis of science.

The history of physics teaches that there have been various examples of great scientific changes preceded and accompanied by epistemological considerations; the birth of modern physics was conditioned by profound changes of a philosophical nature, even if the increasingly marked specialization of knowledge leads to an increasingly clear separation between the two disciplines.

Quantum mechanics appears to be a provisional solution, with a certain degree of inadequacy, to provide a complete picture of the world we live in; however, considering it simply as a calculation tool, extraneous to the real description of the world, is a too suspicious attitude.

There does not appear to be a one-to-one correspondence between the formalism and the experimental results. The introduction of the wave function, following the double-slit experiment, does not exclude the possibility of a description with other types of calculation and with other formalisms.

Quantum mechanics has various interpretations that necessarily lead to central philosophical arguments of external reality realism and empirical anti-realism; these are debates that continue today, regardless of the state of the art of experimental science.

Standard quantum theory has inconsistencies, logical-speculative problems and its interpretation is anti-realist. It is very difficult to find the answers to every problem, but this does not imply that man continues to search and ask questions; it is in the latter ones that the importance and value of scientific research lies.

Regarding the issue relating to indiscernibility, it is necessary to understand the nature of quantum particles, their individuality or otherwise; it is an ontological question. It is also necessary to understand how to distinguish them if they were individual, i.e. an epistemological question.

The spectrum of possibilities leads to four possible cases: quantum particles (a) non-individual and not discernible, (b) non-individual but discernible, (c) individual but not discernible, (d) individual and discernible.

Various arguments still leave the previous cases open to a definitive answer; among them we remember:

- the dissolution of individualities in quantum mechanics which does not fully resolve the Gibbs paradox;
- the substantial difference between classical (accountable) particles and quantum (non-accountable) ones;
- the difficulty in finding a clear logical language useful for talking about such ontological meta-properties.

The critical issues posed by quantum mechanics on the principle of identity of indiscernibles are partially resolved by the "weak discernibility" [80], through the introduction of a weak discernibility to overcome recent objections [81] to the work of weak discerners [82,83].

The possibility of treating identity through different degrees of discernibility, passing through the forms of weak discernibility up to the absolute discernibility given by the "principle of identity of indiscernibles", are put to the test in quantum mechanics and this principle seems apparently violated. To avoid basing distinguishability on hidden properties, it would be better to give up this principle [84], but it seems to be something necessary [85]. Various other attempts to save the notion of individuality have been made and are being studied [86–90].

In addition to the problem of individuality among indistinguishable particles, in quantum mechanics there is also the problem linked to the individuality of "particular states" of particles, with emergent properties, which belong to sets of particles but are not determined by the individual constituent particles, such as the entanglement [91]. A possible solution can come from considering the concept of space-time as an "a-posteriori", a relational concept that vanishes in the light of considerations linked to the properties of a primordial space [49].

Even if quantum mechanics will likely prove to be inaccurate in the future, it nevertheless remains a valid and rich starting point for doing good and interesting philosophy. The right position to take could be that of the anti-realists, according to whom all theories inform us about how reality should be, but never how it actually is.

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