Reviews on Key Issues in Religion and Science

with Bert H. Hodges, "Language as a Values-Realizing Activity: Caring, Acting, and Perceiving"; Claudia E. Vanney, "Is Quantum Indeterminism Real? Theological Implications"; and Robert A. Segal, "The Modern Study of Myth and Its Relation to Science."

IS QUANTUM INDETERMINISM REAL? THEOLOGICAL IMPLICATIONS

by Claudia E. Vanney

Abstract. Quantum mechanics (QM) studies physical phenomena on a microscopic scale. These phenomena are far beyond the reach of our observation, and the connection between QM's mathematical formalism and the experimental results is very indirect. Furthermore, quantum indeterminism defies common sense. Microphysical experiments have shown that, according to the empirical context, electrons and quanta of light behave as waves and other times as particles, even though it is impossible to design an experiment that manifests both behaviors at the same time. Unlike Newtonian physics, the properties of quantum systems (position, velocity, energy, time, etc.) are not all well-defined simultaneously. Moreover, quantum systems are not characterized by their properties, but by a wave function. Although one of the principles of the theory is the uncertainty principle, the trajectory of the wave function is controlled by the deterministic Schrödinger equations. But what is the wave function? Like other theories of the physical sciences, quantum theory assigns states to systems. The wave function is a particular mathematical representation of the quantum state of a physical system, which contains information about the possible states of the system and the respective probabilities of each state.

Keywords: critical realism; determinism; divine action; epistemology; interdisciplinarity; interpretation; philosophy of science; quantum mechanics; quantum reality; theology and science

For the standard view of quantum mechanics (QM), the wave function describes an ensemble of possible events. However, there is no agreement about its ontological meaning. Some authors claim that wave functions

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are real, while others deny their objective reality. "Quantum states are the key mathematical objects in quantum theory. It is therefore surprising that physicists have been unable to agree on what a quantum state truly represents. One possibility is that a pure quantum state corresponds directly to reality. However, there is a long history of suggestions that a quantum state (even a pure state) represents only knowledge or information about some aspect of reality" (Pusey, Barrett, and Rudolph 2012, 475).

While technological applications of QM are abundant and extremely effective, theoretical interpretation is a great challenge. Measurement is, in general, the experimental determination of the value of an observable quantity, but in a quantum context, measurement may yield a variety of possible outcomes. The core quantum measurement problem is to understand why a specific result is obtained on a specific occasion.

It is widely agreed that the measurement problem is the theory's main interpretative concern. It played a central role in debates between Albert Einstein and Niels Bohr, setting the scene for the various paradoxes of the theory (e.g., Schrödinger's cat paradox and the Einstein-Podolsky-Rosen paradox) (Wheeler and Zureck 1983). The measurement problem also raises broader issues (Born 1953; Krips 2013), such as the philosophical debate between realism (objects exist independently of our observations) and antirealism (the acts of measurement are constitutive of phenomena), which impact the dialogue between science and religion. Furthermore, as we shall see, different interpretations of quantum theory have various theological consequences as well.

This paper offers a review of several questions QM poses to theological discussion. The first section presents some of the most relevant interpretations of QM, providing a brief description of the key points discussed in further sections, but also suggesting additional bibliography for a fuller understanding of each specific interpretation. In the second section, I approach the question of quantum indeterminism to show that QM does not provide a unanimous answer. For some interpretations indeterminism is real, whereas for others it is only apparent. This brings us to the question about the kind of knowledge that science can obtain. As this issue should be framed within the scientific realism–antirealism debate, the most relevant viewpoints of this discussion are also mentioned. The third section considers the potential theological implications of quantum indeterminism. Given the plurality of interpretations and ontologies arising from QM, the fourth section discusses whether it makes sense to inquire into the theological implications of the quantum world. I suggest that an ontological-pluralist view is characteristic of how science objectifies reality, but is not necessarily present in other kinds of knowledge, such as metaphysics or theology.

Some Interpretations of Quantum Mechanics

The Copenhagen interpretation. The first interpretation of QM was the Copenhagen interpretation, which was born in the 1920s and was unitarily presented by Heisenberg in 1955 (Heisenberg 1958). It is comprised of a cluster of shared ideas among a group of thinkers (i.e., Niels Bohr, Werner Heisenberg, and Max Born), united by the determination to defend QM as a complete and correct theory (Howard 2004; Faye 2014). For the Copenhagen interpretation, the quantum state is a catalogue of probabilistic dispositions (Born-rule probabilities). For each quantity (position, energy, momentum, etc.), the state defines a probability distribution on all possible values of the quantity. In 1927, Heisenberg proposed the projection postulate or "collapse of the wave function" in the process of measurement to account for the passage from the probability distribution of potential values (quantum state before the measurement) to a single measured value (quantum state after the measurement) (Heisenberg 1927).

This collapse is not a consequence of the Schrödinger equation, but it must be imposed on the theory as an extra condition. Although all quantum systems are a superposition of their possible states, through measurement they are "collapsed" or projected to the measured state. In other words, during the measurement process, the system randomly adopts one of the potential states in a nonlinear indeterministic evolution. According to the Copenhagen interpretation, the interaction between the system and the observer (or the measuring device) causes the collapse of the wave function into a single result. Many philosophers and physicists have identified the Copenhagen interpretation with the mysterious collapse of the wave function in the measurement's process.

Idealistic interpretations. Although Bohr and other founders of the theory categorically denied the ontological thesis that the subject has any direct impact on the outcome of a measurement, the hypothesis of the collapse also led to some idealistic interpretations of the theory. In 1932 John Von Neumann provided a rigorous axiomatic treatment of QM within the framework of Hilbert's spaces (Von Neumann 1955). In this work he also addressed the problem of quantum measurement, arguing that the measurement of an observable quantity of a physical system is completed only when the result of the observation is registered by the observer's consciousness. "Experience only makes statements of this type: an observer has made a certain (subjective) observation; and never any like this: a physical quantity has a certain value" (Von Neumann 1955, 420). After this seminal work, some authors, such as Eugene Wigner (1967) and John Wheeler, also attributed the collapse of the wave function to the consciousness of the observer. "No phenomenon is a phenomenon until it is an observed phenomenon" (Wheeler 1978, 43).

Without going any further, the problem of quantum measurement points out an important fact: during the measurement process, there is an interaction between the (micro) measured system and the (macro) measuring apparatus. In other words, the system is not isolated when the measuring takes place. Measurement "implies the impossibility of any sharp separation between the behavior of atomic objects and the interaction with the measuring instruments which serve to define the conditions under which the phenomena appear" (Bohr 1958, 39–40). However, to admit that physical phenomena are mutually interconnected does not necessarily mean that they depend intrinsically on the mind or consciousness of the observer, as claimed by the idealistic interpretations (Shimony 1963, Nauenberg 2007). As Hilary Putnam expresses it: "measurements are a subclass of physical interactions—no more or less than that. They are an important subclass, to be sure, and it is important to study them, to prove theorems about them, etc.; but 'measurement' can never be an *undefined* term in a satisfactory physical theory and measurements can never obey any 'ultimate' laws other than the laws 'ultimately' obeyed by *all* physical interactions" (Putnam 2005, 618).

Statistical or ensemble interpretations. The above-mentioned interpretations of QM consider that wave function describes completely all the features of an individual system. Statistical or ensemble interpretations, instead, assume that the wave function does not refer to a single system, but to an ensemble of similarly prepared systems. Max Born was the first to propose that the wave function does not refer to an individual experiment, because it would be the statistical result of many (Born 1955). He emphasized the distinction between an ensemble (a conceptual set of replicas of one particle in its experimental surroundings) and a beam of particles (which is a different kind of many-particle system). The statistical interpretations assume the wave function as an abstract statistical function, which only applies to similar procedures that are repeated (Ballentine 1970). These interpretations consider indeterminacy as a statistical dispersion principle. However, the introduction of hidden variables to determine the outcome of individual events is also fully compatible with the statistical predictions. The ensemble interpretations include a large number of different proposals, which highlight the idea that QM is fundamentally a classical theory of a probabilistic or stochastic process (Home and Whitaker 1992).

Bohmian mechanics. Some physicists, such as Albert Einstein, resisted the indeterminism of QM, and held that indeterminism is not a characteristic of nature, but only a consequence of our ignorance (Einstein 1935). According to them, quantum indeterminism appears because QM is not a complete theory. The aspiration of these researchers is to find a new theory, which reconnects microscopic objects with deterministic laws and not chance. David Bohm, for example, developed an innovative formalism for QM that postulates the existence, at a lower level, of certain "hidden variables" (variables without empirical access) which integrate the quantum state (Bohm 1952a,b). Therefore, the hidden variables complete the information given by the wave function fixing the paths of the particles and restoring determinism at the microphysical stage. "Bohmian mechanics is the minimal completion of Schrödinger's equation, for a nonrelativistic system of particles, to a theory describing a genuine motion of particles" (Goldstein 2013). Thus, for this version of QM, probabilities arise from an unavoidably ignorance of certain relevant factors. Bohmian mechanics is "nonlocal" (i.e., connections would be propagated instantaneously), completely deterministic, and empirically indistinguishable from standard QM (Bohm and Hiley 1993). There are various interpretations of Bohmian formalism (Belousek 2003), which provide different ontologies for Bohmian mechanics (i.e., monism of particles (Dürr, Goldstein, and Zanghi 1992), dualism of pilot-waves and particles (Valentini 2010), radical dualism of universal wave-function and universal particle (Albert 1996)).

Many-worlds interpretations. In contrast to statistical interpretations, the many-worlds approach to QM asserts the objective reality of a universal wave function: all quantum states are realized in infinitely bifurcating worlds. In 1957, Hugh Everett proposed that there are many other similar worlds in the universe (in addition to the world we are aware of), which exist in parallel in the same space and time (Everett 1957, Vaidman 2014). The many-worlds proposal is a deterministic theory (the universal wave function always evolves according to the Schrödinger equation), which denies the actuality of wave function collapse by replacing the collapses with quantum decoherence (i.e., the interactions between a system and its environment that lead to a suppression of interference phenomena, to recover an almost-classical pattern of probabilities) (Bacciagaluppi 2012). There are numerous variations and reinterpretations of the original Everett ideas (Barrett 2003). The many-worlds concept has become enormously influential in theoretical physics, but remains highly controversial (Saunders et al. 2010).

Modal interpretations. Modal interpretations are another family that was born in the early 1970s (van Fraassen 1972; Vermaas 1999). They focus their attention on the properties of physical systems, and do not assign a special significance to the measurement process. Like Bohmian mechanics and Everett's many-worlds, modal interpretations deny collapse. "A quantum measurement is an ordinary physical interaction. There is no collapse: the quantum state always evolves unitarily according to the Schrödinger equation" (Lombardi and Castagnino 2008, 383). A specific feature of this approach is the distinction between the "dynamical state" (which determines which physical properties the system may possess, and which it may have at later times) and the "value state" of a system at any instant (which represents all the system's physical properties that are sharply defined at the instant in question). On the one hand, modal interpretations are realist, in the sense that they assume that quantum systems possess definite properties at all instants of time. Thus, each modal interpretation supplies an "actualization rule," which picks out, from the set of all observables of a quantum system, the subset of definite-valued properties (Lombardi and Dieks 2014). On the other hand, according to modal interpretations, the dynamical state constrains possibilities rather than actualities: "the state delimits what can and cannot occur, and how likely it is—it delimits possibility, impossibility, and probability of occurrence—but does not say what actually occurs" (van Fraassen 1991, 279). In other words, despite denying the collapse, indeterminacy is a feature of our world for modal interpretations, because the future is not simply unknown, but it is potential or not yet decided. Moreover, since there are several options open, opportunities also exist for the emergence of innovations.

Among the various interpretations of QM, modal interpretations offer an interesting framework to analyze the metaphysical and theological implications of QM. Unlike the Copenhagen interpretation and the idealist ones, modal interpretations deny collapse, offering a realist comprehension of the theory. Furthermore, unlike other realist interpretations, such as Bohmian mechanics or many-worlds, modal interpretations propose an indeterminist ontology. Despite not being an objective explicitly sought by philosophers of physics working on modal interpretations, in my opinion these interpretations are more compatible than others with classical metaphysics, and they offer a space for fruitful theological reflection. For example, the modal distinction between "dynamical state" and "value state" admits a parallelism with the Aristotelian notions of potency and act. In an Aristotelian view, potency and act are coprinciples of real things, so that there would be potentiality (indeterminacy) and actuality (determination) at the same time. And, as we will see in the next sections, the existence of determination is compatible with design, and the existence of indeterminacy is compatible with noninterventionist divine action.

Is It Possible to be a Realist about Quantum Mechanics?

It is widely accepted that there are radical differences between the macroscopic world of Newtonian physics and the microscopic world of QM. Although this is not entirely accurate (Lombardi 2002), it is usually considered that the macroscopic world is deterministic, because in Newtonian physics inexorable laws govern the movement of the whole cosmos. So if the previous state is known, we can predict the future. Instead, QM introduced randomness in the prediction of the events that occur in the atomic and subatomic levels. However, is it possible to be realist about quantum indeterminacy? As we have seen, the answer depends strongly on the interpretation of QM adopted. To some interpretations (e.g., the Copenhagen interpretation and modal ones), quantum indeterminism is an intrinsic property of the natural world. Other interpretations, however, consider that quantum indeterminism is a mere manifestation of our ignorance or a consequence of the limitations of the current theories (e.g., Bohmian interpretation and the evolution of the whole universe in the Everettian ones). A third group argues that scientific theories—including QM—can neither affirm nor deny the determinism or the indeterminism of the natural world (e.g., some statistical interpretations).

Nevertheless, is quantum indeterminism real or only apparent? Some authors tried to classify not only QM, but also diverse other physical-mathematical theories into deterministic or indeterministic. It is usually considered that dynamic equations of motion are deterministic when a given value of independent variables univocally fixes the dynamic evolution of a physical system in any given state. In this way, the deterministic character of a certain scientific theory, or the lack of it, will usually be associated with the possibility of finding unique solutions for dynamic equations: if the possible solutions are not unique, there will be no determinism (Earman 1986). However, the above-mentioned classification is not easy to accomplish because each of the different theories includes notions—such as "system" or "state"—which are not defined with the necessary precision. We saw, as an example, the difficulty in defining the quantum state. Hence, even within each theory there will be an open space to formulate legitimately a notion of determinism in different ways, thus requiring an interpretative discernment to choose the best formulation in each case (Bishop 2005). Therefore, in order to affirm the determinism or indeterminism of a given scientific theory, it is necessary to move forward to an in-depth study of the kind of reasoning behind scientific theories and this requires adopting a meta-theoretical epistemological perspective.

Another generally accepted claim by scientists is that Newtonian physics is realistic, since it assumes that scientific theories describe the world regardless of the observer. In various interpretations of QM, however, the observer plays an important role in the measurement process. Until the late nineteenth century, it was commonly assumed that scientific models provide knowledge of different aspects of the world, including unobservable aspects, and helped to understand the structure of the universe. Nevertheless, many experiments showed that the quantum world defies common sense interpretation (Shimony 2001), fostering philosophers to rethink the nature of scientific knowledge and reality.

Scientific realism is an epistemic positive attitude towards the content of our best theories and models, which yield knowledge of aspects of the world, including unobservable aspects (Chakravartty 2014). The multiple scientific realisms fall into three basic varieties (Merrill 1980). Metaphysical realism is a position regarding how our theories are related to the world:

the entities postulated by a scientific theory have a mind-independent existence. Semantic realism is a view concerning how theories are to be interpreted: scientific claims should be construed literally as having truth-values, whether true or false. Epistemic realism is a position concerning what the acceptance of the theory means: our best scientific theories give true (or approximately true) descriptions of a mind-independent world.

By contrast, throughout the twentieth century, a variety of rival epistemologies of science, known collectively as forms of scientific antirealism, began to emerge as well (Niiniluoto 1999, 9–13). Scientific antirealists do not seek a correspondence between scientific theories and reality. Among them, instrumentalists deny that theoretical statements have a true value (Carnap 1966). They consider that they are merely instruments for predicting observable phenomena or systematizing observation reports. Scientific theories would only be suitable human constructions, mere practical tools to achieve a predictive or technical control of reality. Scientific models are imaginative fictions, used in the construction of theories and usually then discarded (Vaihinger 1924). Skeptics deny the possibility of true knowledge or progress toward it (Feyerabend 1987). Kantians maintain that although a mind-independent reality exists, it is "veiled" from our eyes (d'Espagnat 2011). Pragmatists replace the realist concept of truth as correspondence with some epistemic substitute (i.e., coherence (Rescher 1973), consensus (Rorty 1998), among others). Methodological nonrealists regard the truth of the theories as inaccessible, and replace it with an epistemic surrogate, such us successful prediction (Laudan 1981) or simplicity (Goodman 1972). Historicists consider that empirical reality is structured by scientific paradigms (Kuhn 1996). For constructive empiricists, theories should have to save the appearances. Theories have a true value but it is irrelevant for the aims of science (van Fraassen 1980). All these proposals, among others, deny metaphysical, semantic and/or epistemic realism, although some of them may accept semantic and/or epistemic ones.

An intermediate position between classical realism and instrumentalism is critical realism, which considers that the primary aim of science is to explain the world, and that scientific theories are limited representations of the world. Critical realism assumes "ontological realism (that there is a reality, which is differentiated, structured, and layered, and independent of mind), epistemological relativism (that all beliefs are socially produced and hence potentially fallible), and judgmental rationalism (that despite epistemological relativism, it is still possible, in principle, to provide justifiable grounds for preferring one theory over another)" (Patomaki and Wight 2000, 224). For critical realism "truth is not easily accessible or recognizable, and even our best theories can fail to be true. Nevertheless, it is possible to approach the truth, and to make rational assessments of such cognitive progress. The best explanation for the practical success of science is the assumption that scientific theories in fact are approximately true or sufficiently close to truth in the relevant aspects. Hence, it is rational to believe that the use of the self-corrective methods of science in the long run has been, and will be, progressive in the cognitive sense" (Niiniluoto 1999, 10).

Nancey Murphy remarks the importance to block the move to relativism based on the recognition of the plurality of perspectives and the historical and social conditioning of knowledge, and suggested a new definition of "true." According to her, "a true statement (theory) is one that provides (one of) the best solution(s) to an empirical-conceptual puzzle" (Murphy 1989 308). In my opinion, a proposal that goes beyond critical realism, besides explaining the scientific knowledge, should also admit the possibility of abandoning the Kantian framework to attain knowledge of metaphysical principles. An attempt in this direction can be found in Leonardo Polo's epistemology (1984–1996). This Spanish philosopher argues that knowledge has two dimensions in perfect agreement: one is the cognitive act (methodic dimension), and the other one is the content known (thematic dimension). So, knowledge "is an act that is unitarily thematic or a theme that is unitarily an act" (Polo 1987, 79). In other words, no theme appears without accounting for the intellectual method that led to its consideration, and there is no intellectual act that does not delimit its theme in a clear way. Polo distinguishes several kinds of cognitive acts, and he points out that no cognitive level can be considered absolute. Polo proposed a methodic-thematic pluralism, which not only relates the gnoseological (methodic) to the ontological (thematic) realms without confusing them, but also paves the way to establish the cognitive status of different disciplines avoiding reductionism. Consequently, scientific knowledge would require the use of specific cognitive acts, accessing knowledge of reality with the limitations identified by critical realism. However, Polo also proposed an appropriate intellectual method to attain metaphysical knowledge, which differs from scientific objectification (Vanney 2008, 2014).

There are general philosophical reasons for regarding realism as an attractive position, but QM strongly puts the realistic conviction to the test. Therefore, is it possible to be a realist about QM? Again, the answer depends strongly on the interpretation of QM adopted. Many antirealist or ontological-relativist approaches to philosophy of science were vigorously influenced by the Copenhagen instrumentalist stance, which reject any question of reality beyond QM appearances. However, other interpretations, such as Bohmian or many-worlds, offer a realistic interpretation of the quantum world consistent with the QM predictive-observational data (Norris 2000). In general terms, those who clung tightly to realism argue that the earliest formulation of QM did not provide a complete description of atomic systems. Nevertheless, many physicists refuse to postulate entities that are neither observed nor needed, and prefer the family of Copenhagen-like interpretations. For them, our knowledge of reality is "weakly objective"; that is, we may obtain some limited knowledge of the underlying quantum reality through their manifestations in interaction with our instruments of observation, because reality exists independently, regardless of our recognition of it, which is partially responsible for what we observe in macrophysical or microphysical levels (Stoeger 2001).

Theological Implications

The antirealist approaches to philosophy of science tend to accentuate the conceptual limitations of human knowledge. Some scholars have extended the instrumentalist worldview of QM to other disciplines such as theology. "According to the instrumentalist construal of theological discourse, statements of that discourse are not capable of being true or false, so the question of whether or not a conjunction of theological propositions can be true does not arise. Instrumentalism, it seems, thus insulates theistic discourse from contradiction" (Le Poidevin 2003, 276). If this position were assumed, neither science nor theology would be able to provide significant information about the real world, and a meaningful dialogue between them could not be possible. There have been different responses to this proposal. Benjamin Cordry, for example, explained that religious fictionalism must address significant philosophical difficulties, including issues of justification, meaning, and interpretation (Cordry 2010). Jerome Gelman argued that the initial attractiveness of theological realism can be reestablished by a logical reconstruction of the realist approach to religious language (Gelman 1981).

However, the stimulating controversies which quantum indeterminism has opened among scientists, philosophers, and theologians do not only apply the epistemology of scientific realism, but also deal with the meaning of causality and divine action in the natural world. Even though these issues were discussed at length during the last century, many of them continue to be unresolved.

The deistic watchmaker God. During the eighteenth and nineteenth centuries, the universe was compared to a large mechanical clock. As Wolfhart Pannenberg highlights, the most important issue between science and theology throughout their modern history relates to the mechanistic interpretation of nature (Pannenberg 2006). This understanding led to the deist conception of a watchmaker God, who created the cosmos and let it evolve by itself, ignoring it. This deistic thesis, also supported by some liberal protestant theologians such as Friedrich Schleiermacher (1956, §46), Rudolph Bultmann (1953) and Gordon Kaufman (1968), has strong theological implications. A causally closed view of nature confronts theology of divine action, and forces choice between two alternatives: (1) noninterventionism: God only sets the world's initial conditions (i.e., if mechanical laws rigidly determine the course of the universe, there is no room for a provident God's action without a violation of the laws of nature);

(2) objectively special divine action: God really intervenes in the natural order either by violating or by suspending the ordinary laws of nature. Since quantum indeterminism was a serious obstacle for the mechanistic determinism in the early twentieth century, scientists, philosophers, and theologians often have seen in QM the promise of a genuine openness in nature for the discussion of free will and of divine action.

The "Scientific Perspectives on Divine Action" project. In 1958 William Pollard suggested that quantum indeterminacy was the domain through which divine providence works in the government of all events (Pollard 1958). In the last thirty years, the research program called "Scientific Perspectives on Divine Action" has studied various areas of contemporary science that offer different spaces of indeterminacy to explain divine action in the natural world (Wildman 2004; Russell, Stoeger, and Murphy 2009). Several researchers of the "Scientific Perspective on Divine Action" project argue that God, by selecting the laws of nature, chose very specific laws with remarkable properties, allowing a genuine emergence of complexity and indeterminism in nature, which go beyond a mere display of the consequences of the laws (Murphy 2010). In particular, Robert John Russell claims that QM provides a good framework to propose an "objectively special noninterventionist divine action" (Russell et al. 2001).

It is important to remark that this project assumes an intrinsic indeterminism in nature, preferring the interpretations of QM that accept the projection postulate. According to Nicholas Saunders, the possibilities for divine interaction with quantum mechanics fall into four main categories: (1) God alters the wave function between measurements; (2) God makes God's own measurements on a given system; (3) God alters the probability of obtaining a particular result; and (4) God controls the outcome of measurement (Saunders 2000). However, each of these alternatives has led to problematic issues. Some of them depend critically on the ontological status of measurement probabilities in quantum mechanics, and others are highly interventionist actions.

> The thesis that God determines all quantum events is not only scientifically irreconcilable with quantum theory but also theologically paradoxical.... If God did act regularly in quantum mechanics, then there are relatively few quantum processes that would escape such control. If this is the case, it seems very irrational that God would formulate quantum mechanics, as a product of the creation of the world, to be indeterminate.... Indeed, if we were to couple the proposals discussed here with a common interpretation of the quantum measurement problem, we would reach the absurd conclusion that God is often prevented from acting in the universe because of the lack of anyone to perform a measurement. (Saunders 2000, 541–42)

Other scholars have pointed out that quantum indeterminacy is not an indispensable requirement to support the action of God in the natural world.

When it is assumed that the action of God requires "gaps of indeterminacy" in scientific laws or the existence of regions where the causality is not well defined, the understanding of causality is rather ambiguous, lacking an accurate distinction between divine causation and created causation. Likening divine action and natural action is also a source of new challenges. If the causal status of God is thought of as that of any other cause, divine actions lose their provident nature. It is difficult to understand how a cause, which is only one cause among others, can guide the created world to its final destination (Silva 2014).

Chance and God's purpose for the cosmos. Opposing the aforementioned positions, some researchers attributed the collapse of the wave function not to divine action, but to a mere matter of chance. However, to argue that quantum phenomena only occur by chance also has theological implications, because it strongly challenges the idea of a divine design in nature or a divine purpose in creation. For this reason, most of the materialistic thinkers assume that our world is not the result of a divine purpose but a mere product of chance, as a basic premise (Monod 1970, Dawkins 1988, Dennett 1995). Theology has given different answers to this proposal. Some theologians directly attribute to God the determination of the possibilities that quantum indeterminacy leaves open (e.g., many researchers of the Divine Action Project). Others, however, argue that both law and chance integrate the divine plan, because God has created the universe as a self-organizing process. God gives a purpose to the cosmos, but without determining the exact sequence of events in a direct way. "God allows a degree of open-endedness and flexibility in nature, and this becomes the natural, structural basis for the flexibility of conscious organisms and, in due course and more speculatively, possibly for the freedom of the human-brain-in-the-human-body, that is, of persons. . . . So it does help us to perceive the natural world as a matrix within which openness and flexibility and, in humanity, perhaps even freedom could naturally emerge" (Peacocke 1995, 281).

Quantum holism and top-down causation. Besides indeterminacy, QM also has another peculiarity, which is "quantum entanglement" (Bub 2014). Many-particles states cannot be expressed as a simple product of one-particle states, but only as a superposition of such products including an interference term. In 1935 Erwin Schrödinger also explained that when two particles had a temporary physical interaction, they should be described by a single wave function (Schrödinger 1935). Consequently, when a quantum system interacts with another at any moment, both systems continue to maintain an amazing correlation. In other words, the entanglement persists even when being separated across large distances ("nonlocality") (Aspect, Dalibard, and Roger 1982). However, since "nonlocality" could be understood as instantaneously causal action-at-a-distance (as in Bohmian mechanics), with the risk of violating the spirit of special relativity, some authors argue that it is better to assume a "holistic nonseparability" in the interpretation of QM (Redhead 2001).

Just as indeterminacy did, quantum entanglement also offers new perspectives on reflection about the meaning of causality and divine action in the natural world. In Newtonian physics, a system can be analyzed into parts, whose states and properties determine those of the whole they compose. However, the entangled states in quantum mechanics resist such analysis, opposing Newtonian physics' methodological reductionism (Healey 2009).

Some scholars have pointed out that the holistic character of quantum theory "is consistent with a multilevel view of reality and the emergence of new kinds of events at higher levels of organization" (Barbour 2000, 89). However, this statement does not imply reductionism (Gershenson 2013). There is a naturally strong sense in which particle physics as described by quantum field theory underlies atomic physics. In a broadly similar way, atomic physics underlies chemistry, and chemistry underlies biochemistry. Nevertheless, it is important to highlight that these inter-theoretic relations vary in the abovementioned cases, and that they do not provide neat examples of the traditional philosophical conception of theory-reduction—that is the deduction of one theory from the other, accompanied by judiciously chosen definitions of terms. "We must expect the 'higher' levels to contain much (in terms of structures, concepts or explanations) that is distinctive, giving them a high degree of 'autonomy' from the 'lower' levels" (Butterfield 2001, 113–14).

At the microphysical level, constituent units of a system are what they are because of their incorporation into the system as a whole, which exerts precise constraints on its units ("top-down" causation), making them behave otherwise than they would in isolation. "In addition to bottom-up causation, *contextual effects* occur whereby the upper levels exercise crucial influences on lower level events by setting the context and boundary conditions for the lower level actions. This is related to the emergence of effective laws of behavior at higher levels that enable one to talk of existence of higher level entities in their own right. They then play an effective role not only at their own levels, but also influence the lower levels by setting the context for their action" (Ellis 2012, 1896).

Some theologians, like Arthur Peacocke, suggested that the way in which top-down causation operates provides a new comprehension about how God could interact with nature, preserving in some way divine transcendence. "If God interacts with the 'world' at this supervenient level of totality, then he could be causatively effective in a 'top-down' manner without abrogating the laws and regularities (and the unpredictabilites we have noted) that operate at the myriad sublevels of existence that constitute that world" (Peacocke 1993, 159).

As we can see, each theological proposal discussed in this section assumes a specific interpretation of the quantum theory and often also a different ontology. In light of this, it is reasonable to ask whether it is meaningful to inquire into the theological implications of the quantum theory.

Does it Make Sense to Inquire into the Theological Implications of the Quantum World?

Science and theology are different kinds of knowledge, and QM provides a new epistemological approach to justify interdisciplinary perspectives. In 1927, Niels Bohr presented at Como the "principle of complementarity." According to this principle, QM involves mutually exclusive models of description, each complete in itself and complementary to the other mode (Bohr 1928). As the atomic world cannot be described using classical notions; it is necessary to choose between a wave model and a corpuscular one, between a causal and a temporal–spatial description, between accurate knowledge of the position of a particle and its velocity. Bohr also suggested extending the idea of complementarity to other phenomena, such as the organic models in biology, dialectic argumentations in sociology, and the behavioral and introspective models in psychology (Bohr 1937, 1950).

Some authors have proposed extending QM's principle of complementarity to the relationship between science and theology, arguing that both disciplines study the same reality, but under complementary perspectives. "Physicists have popularized this term to represent the relation between 'wave' and 'particle' aspects of the behavior of light without fully understanding it. Why should not the theologian ease his conscience by following in such distinguished footsteps and broadly declare his theological statements and those made in other disciplines to be simply 'complementary'?" (MacKay 1974, 225).

However, the extension of complementarity to the relationship between science and theology presents several problems. Ian Barbour warned that it should be used with caution, since complementarity involves the consideration of alternatives that come from the same logical level, and this does not apply to science and religion (Barbour 1974, 77–78). Therefore, for Barbour, the assumption of an overly broad interpretation of the principle of complementarity runs the risk of admitting uncritically inconsistent dichotomies, which could emerge from nonoverlapping magisteria (Barbour 2000, 77). In response to this objection, K. Helmut Reich suggested distinguishing between "logical or parallel complementarity" and "epistemological complementarity." For Reich, the second option, that is "to think in terms of complementarity," could also be applied to hierarchical levels, serving as a fruitful heuristic and cognitive device for gaining a deepened understanding of several problems (Reich 1990). I agree with Reich´s distinction, but I think that such an "epistemological complementarity" requires a more comprehensive theory of knowledge than critical realism.

If some difficulties appear in the relationship between science and theology in general, the situation is even more intricate when it is applied to QM. While there are no important disagreements among physicists on the use of QM, disputes on the meaning of quantum physics began with its inception and continue today. Given the multiple interpretations of QM, it is feasible for scientists to make only a pragmatic use of mathematical formalism, without assuming (tacitly or explicitly) its ontological implications (Healey 2012). Undoubtedly QM represents a significant expansion of scientific knowledge, but as physicists' daily research is mainly directed towards specific ends, it is possible for them to avoid questions about the ontological meaning of quantum formalism (Fuchs and Peres 2000). However, this position is unacceptable for philosophers of physics, who specifically study the foundations of physical theories.

In general, to tell us something about the world, mathematical formalism needs an interpretation in terms of measurable quantities. Through an ontological interpretation, mathematical formalism becomes a physical formalism such us QM. Many philosophers of physics have been involved in the task of interpreting the quantum formalism in the last century. "Otherwise, the debate over interpretations is likely to become isolated from the data of physics (to its own detriment) and unable to offer heuristic ideas to physics (to the detriment of physics)" (Butterfield 2001, 113).

The move from mathematical formalism to its ontological interpretation has always been problematic in mechanics, and is even more acute in QM, where the empirical data underdetermine the interpretative position. The fact that quantum formalism yields very different ontologies (Copenhagen indeterminism, Bohmian nonlocal hidden-variable determinism, many-branched tree in many-worlds interpretations, among others) makes the problem extremely complex. It is undeniable that contemporary physics proposes an ontological pluralism (Lombardi and Pérez Ranzanz 2012). However, could this pluralism be related to a limited access to knowledge of reality through physics? According to John Polkinghorne, the choice between different ontologies has to be made on the basis of extra-scientific criteria, including metaphysical principles. "Science alone will never provide the key to the nature of agency, yet seeks patient clarification of the complex character of physical process as being the best basis for the elaboration of further metaphysical ideas" (Polkinghorne 2001, 190).

Nevertheless, the problem of multiplicity of ontologies still appears to be more critical when we seek to address the theological implications of QM. Ernan McMullin claims that there are important challenges to the relations between QM and theology (McMullin 2001, 55–56). Theology, as well as theoretical physics, often relies on the underlying structure of the world. Because "to serve theological ends, theory has to declare (or at least strongly suggest) how the world is" (McMullin 2001, 55), and the theological implications of the diverse interpretations of QM are considerably different. The warning by McMullin is relevant, but does not necessarily imply the lack of QM's theological consequences. Thomas Tracy comments:

> This interpretative pluralism creates both an opportunity and a hazard for theologians. On the one hand, it is perfectly legitimate under these circumstances for a thinker grappling with the theology of nature to prefer one interpretation to another on theological grounds. Indeed, there can be no theological appropriation of quantum mechanics that does not make use of one or another of the currently viable interpretations. On the other hand, in casting our theological lot with a particular interpretation, we take the risk that new developments in physics or in the philosophy of physics will significantly undercut our theological constructions. (Tracy 2001, 253–54)

Just as philosophers of physics defend the importance of having a consistent interpretation of the mathematical formalism, and metaphysicians the aim to unify the multiplicity of ontologies that follow from the various interpretations of QM, some theologians emphasize the importance of considering the theological implications of the theory. Philip Clayton remarks:

> The conceptual space defined by the quantum mathematical formalism and the associated empirical observations neither proves nor disproves the existence of any divine being. Nor will it, by itself, establish—or rule out—any claim about divine action. But it may tell us something about how a being (human or divine) must act if it acts in the physical world and in conformity with physical laws. That is, the conceptual space of quantum physics may constrain the ways such a being could be manifested and the sorts of actions a human observer could in principle detect. (Clayton 2001, 212)

Moreover, if the constraints imposed by the physical order tell us something interesting about nature, the constraints of physics could represent the context within which God chooses to act. Serious theological positions can be defended in light of science, even with highly speculative conjectures, but we should be aware of the hypothetical and contingent nature of all such theological reflections, as well as of the differences between theology and the sciences (Clayton 2001, 214–15).

Concluding Remarks

A few statements can summarize the results of this investigation. The domain of applications of QM is enormously wide and successful. Therefore, we must indeed take QM as a description of the world. However, as diverse ontologies emerge from different interpretations of QM, it is difficult to find a satisfactory interpretation of the theory. The dissimilar interpretations of QM save the phenomena, but is it sufficient to use an interpretation that only saves the phenomena? Since in QM there is no valid inference from the empirical success of the theory to its ontological truth, the multiplicity of coexisting interpretations highlights the need for a meta-scientific perspective to evaluate the different interpretations of the theory.

As we have seen, QM has renewed the interest in fundamental questions about the natural world, human knowledge and God, topics that concern not only physics, but also philosophy and theology. Although disciplinary views are inevitable in research, fundamental questions require a special approach and a solution that overcomes partial descriptions. Therefore, only an interdisciplinary effort can pave the way for an adequate understanding of the actual complex relationship between sciences.

Natural sciences, philosophy, and theology have distinct cognitive methods, which correspond to different ways in which the mind grasps truth. As every discipline works within the framework of a theoretical doctrine, and with their own methodology and procedures, it is extremely necessary for interdisciplinary work to have a wide and powerful epistemological framework, one that is able to recognize the dissimilar levels of discourse and domains, and to determine the cognitive scope of various contributions. Probably, critical realism is the best proposal available to explain the knowledge of physics, but it is not enough to account without the knowledge of metaphysics and theology.

The contemporary scenario faces us with the following dilemma: should we adopt an ontological pluralism or a cognitive pluralism? If we assume a priori a "cognitive monism"—the only valid or possible knowledge is the scientific one—we may embrace, in the best of cases, different ontological descriptions. On the other hand, if we assume a "cognitive pluralism," we can also admit a metaphysical knowledge of reality, which would lack the constraints of scientific objectification and would be more suitable for theological reflection. But to assume a cognitive pluralism—including not only scientific knowledge but also metaphysical knowledge—demands the development of an appropriate theory of knowledge, a more comprehensive one than critical realism.

In spite of more than a century of discussions, we are still at the very beginning. The understanding of quantum physics is still an open issue and has too many subtleties, making it impossible to accept a trivial solution. Furthermore, QM is only the first step in a series of more general quantum theories, such as quantum field theories (i.e., string theory, loop quantum gravity, etc.), which are the mathematical and conceptual frameworks for contemporary elementary particle physics.

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