How Quantum Theories Explain

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1 Framing the Question

It has become canonical among philosophers of science that explanation is a central goal of science. This view is often pitted against an often opposing view, which states that 'prediction' is the central goal of a scientific enterprise. Quantum mechanics (QM) is not a scientific field accommodating these two goals in harmony with one another, indeed they are immersed in a controversy that is nearing a century of existence.

Shoppers for theories aiming to explain the explanation are not starved for choices. The attempts to establish explanation as a theory go back in history to the ancient Greeks. In this paper I will be mostly concerned with the views expressed by the 20th century scholars whose attempts to devise such an account are intertwined with the developments in the other fields of the philosophy of science. I will contrast Carl Hempels deductive-nomological account of explanation with the 'causation' view advanced by James Woodward and Wesley Salmon. It will be important to discuss the philosophical notion of what a law is and to outline finer nuances of differences of laws of nature versus scientific laws. For that purpose I will refer to the philosophical contributions by David Lewis and David Armstrong[18].

I will be interested in looking at these theories in the setting of quantum mechanics (QM) whose many interpretations have continued to bewilder and confuse scientists and non-scholars alike from the inception of the QM theory to the present day. Most opinion leaders on the subject draw the dividing line between the standard, orthodox interpretation of QM and alternative ontological interpretations. The debate exemplifies the debate between realists and anti-realists as a general matter, however, I will be interested in looking at these discussions from the point of view of the explanation credentials they provide.

The goal of this paper is not to make an original contribution to the determination of whether a particular postulate of QM or its interpretations has the power of law or delineate its specific mechanism. My claim is to point out that in order to count as explanatory in any sense QM formalism needs ontologies attributable to the objects with which it operates. The ontologies, if and when defined, could be at the origin of a causal mechanism and in that sense establish explanatory credentials of QM theories.

2 Brief Mathematical Description of Quantum Mechanics

Despite its manifest successes at predicting the results of experiments QM has been plagued by problems of interpretation since its inception nearly a hundred years ago. The mathematical formalism of QM is necessarily technical but here is what is relevant to our discussion.

The world is represented by functions that in turn are denoted by so-called *wave functions* otherwise known as *state vectors* computed over complex numbers. As vectors they "live" in multi-dimensional *vector space* (*configuration space*, often denoted as *Hilbert space*) and can be represented by an infinite number of *bases sets*. The time evolution of these state vectors obeys in a deterministic fashion a second order partial differential equation (*Schrödinger equation*) in the form of:

$$i\hbar\frac{\partial\Psi}{\partial t} = -\frac{\hbar^2}{2m}\frac{\partial^2\Psi}{\partial x^2} + V\Psi$$

The short hand for the same equation is:

$$i\hbar\dot{\Psi} = \hat{H}\Psi$$

Significantly, this equation is time dependent, i.e. the wave function Ψ that is a solution to it evolves with time taking different shapes based on inputs of time and position.

The observables: position, momentum, energy - are represented by the so-called Hermitian linear operators that act on the Hilbert space - and take on real values only when measured. The observables are the eigen-values of these matrix operators and are necessarily real (indeed, a measurement value of, say, $2i$ would be devoid of meaning) even though the function Ψ is complex-valued.

Significantly, it is impossible mathematically to compute a set of observables for a given time with absolute precision, specifically, the system's momentum and position, due to the so-called quantum uncertainty principle. This restriction on the specification of observables translates into the inability to pinpoint a precise set of initial conditions for the system. This will become important to us during the discussion on causality.

As a further complication, from the inception of QM, accounting for how a completely deterministic "law of motion" (Schrödinger equation) spontaneously breaks down causing a so-called collapse of the wave function has been a subject of controversy. The collapse is non-deterministic, random and unpredictable. How do we have the experience of being surrounded by tables, chairs and other macro objects if all there is in the world are wave functions? Why and how does the transition happen between the state vectors of waves/particles and the deterministic positions and momenta of everyday macro-objects.

Von Neumann's explanation along the lines that during the *act of measurement, a human observer* (the story does not get any easier with a non-human observer) causes the collapse of the wave function leads to a further complication of trying to define at exactly what point the measurement per se causes the *collapse per se*. This, in turn, inevitably prompts the definition of the measurement apparatus that is perceptible to humans and whose definition is required to be defined in macro terms, which leads to the infamous paradox of macro objects (e.g. Schrödinger's cat, measuring pointer) to be in a superposition (being in different states of position and momentum at the same time).

The issue in the philosophy of QM that has for almost a century divided physicists and philosophers into camps whose respective members preach their views with nearly religious fervor is this: do state vectors, otherwise known as wave functions, have ontological status, or are they a mere computational convenience? And if they do not have ontological status, is the Schrödinger equation the only way in which these states (functions) can change, or are there other ontologies that are relevant to the description of the world on this account?

All of the above accounts address the critical question of whether or not QM is a complete theory and as such explains the world around us. If it does, what account of explanation is most acceptable? And if it does not, what, if anything, do we need to complement the theory with in order to establish its explanatory credentials? In order to answer these questions, a whole industry of QM interpretations has evolved over the past century. Christopher Fuchs from Bell Labs makes a telling observation that not a single year has gone by in the last 30 years when there was not a conference on interpretation of QM somewhere in the world[7].

An alternative view is to follow the orthodox interpretation of Niels Bohr that was further perfected by Von Neumann, otherwise referred to as the Copenhagen interpretation. In this view of the QM theory, nothing in this formalism tells us anything about the world; all it is designed to do is to predict the results of the experiments. Indeed, what does it mean "to live in Hilbert space"? It is a mathematical notion, a configuration space, an abstract object, and abstract objects are defined as having zero causal efficacy. Eloquently summed up by Paul Dirac, the approach states, "Shut up and calculate."

If this is all we take QM to be, the question becomes,"What exactly is QM all about?" If we hold that wave functions have no ontological significance, making the whole exercise to be about the results of experiments rather than about explaining physical phenomena per se, does it have any chance of being called a theory at all?

3 Significance of QM Interpretation for Explanation

The Copenhagen (standard) interpretation (CI) allows us to make predictions about phenomena but makes no claims about the underlying reality. In doing so it comes into a philosophical conflict with ontological interpretations of QM characterized by their attempt to *explain* the state of the world. While the claim that the CI makes is modest - prediction of experimental results - its adherents imply that the limit has been reached with regard to the understanding of reality thus curtailing all further discussions - a position many philosophers of science consider metaphysically unsatisfying. More importantly for this argument, the controversy spawned a second debate immediately relevant to our topic: how exactly should quantum theories explain?

Let us digress here for a quick discussion of the type of philosopher for whom the above questions present a challenge. Hillary Putnam states that the challenge is relevant only to those scientists who view scientific theories from the position of scientific realism. The dictionary definition of scientific realism centers on a positive epistemic attitude toward the content of our theories and models, stating that both observable and unobservable aspects of the world are described by the sciences. [22]

A telling quotation from Putnam states:

The correct view is that when the physicist talks about electrical charge, he is talking quite simply about a certain magnitude that we can distinguish from others partly by its formal properties (e.g., it has both positive and negative values, whereas mass has only positive values), partly by the system of laws this magnitude obeys (as far as we can presently tell), and partly by its effects. All attempts to literally translate statements about, say, electrical charge into statements about so-called observables (meter readings) have been dismal failures. [25]

In this account, scientific theories have both observable and unobservable content. Taking this view further, unobservables are relevant only inasmuch as they have ontological status and can form relations with observables such that they verify claims about them by making observations. QM theories that we will consider define ontologies and establish the metaphysical status of both particles and waves. In doing so they try to account for both the observed and the unobserved phenomena.

My view is that the driving motivation for these pursuits was the lack of acceptance by the post-Heisenberg and Von Neumann group of physicists and philosophers of the mathematical postulates of QM as laws. Indeed, if establishing law-like nature of the Schrödinger equation becomes theoretically untenable, we should discard this view altogether and proceed toward other interpretations that would give us the framework to evaluate the explanatory potential of QM.

4 Accounts of Explanation

Categorizing the theories of explanation may be a credible scientific venture in its own right, however, the ensuing discussion will not suffer from the oversimplification of dividing the adherents into two broad groups.

Let us take a closer look. I will start with a brief discussion of what is generally taken to be a law to see if QM can tackle the issue of explanation from that angle.

4.1 Law

One camp of scholars has attempted to show that the event or phenomenon being explained (*explanandum*, in Hempel's parlance) is *to be expected* from the set of preceding arguments (*explanans*). The proponents of this approach are trying to establish a link between what is being explained and the set of laws, laws being defined with varying degrees of rigidity. [14]

As we will need to use the term extensively, I will pause here to mention the relevant attributes of the law. At the highest level, laws are generalizations. A simple example would be the laws of gravitation and, say, the laws of thermodynamics. Laws can either be restricted in their application or be universal, but, importantly, they are thought of as not being in need of further explanation. This is a crucial point, as non-law-like generalizations require further elaboration. Elliptical trajectories of planets are not postulated as being a law as such, but are explained by Newtons laws of gravity.

The history of science is fraught with examples of accidental generalizations being taken for laws, prompting a more elaborate set of definitions. According to the systems approach espoused by Lewis, laws are composed of the axioms that are taken to be true, and theorems are the logical consequences of these axioms. Laws possess two competing qualities, simplicity and strength, and they, according to Lewis, provide for the optimal combinations of these qualities[18]. The practical application of this latter proposition by Lewis has been criticized for the subjective nature of defining what simplicity and strength are taken to mean.

David Armstrong pioneered an alternative approach based on the appeal to universals. In his view, laws establish a "relation of non-logical or contingent necessitation"[3] and in so doing are supported by counterfactuals (if X, then Y; if not X, then not Y). Crucially, Armstrong also believed that one of the requirements for a law-like relation is causality.

Other philosophers such as Cartwright and Woodward opined that laws need to describe causal powers in order to serve as tools for explanation[30].The reason behind this view is, absent a causal mechanism, the risk increases of attributing a law-like status to an accidental generalization arrived at purely on the basis of empirical observations. We will see that this will turn out to be a particularly controversial topic in QM

Some philosophers go further in restricting what kinds of generalizations could be called laws. For example, Earman and Roberts state that laws should be true "without equivocation, qualification, proviso or ceteris paribus clauses[6]. In this view, very few generalizations could be called laws unless the inevitably restricted application of the concept renders the notion useless. Indeed, for our purpose, it makes sense to keep in mind what we need the concept of a law for. Let us be reminded that we are simply intending to show that the phenomenon we describe is predicted by and falls within a certain generalization that does not require further explanation. On this account, we need to be looking for certain features of law-hood such as described above, but we will have to take a view whether, on balance, as a combination of characteristics that we find, a QM interpretation in question should be deemed in need of further explanation or whether it could be proclaimed a law with a full stop on further discussion.

As a side note, we should distinguish between what we take to be scientific laws versus what are taken to be laws of nature. Laws of nature are universal generalizations that are exceptionless, and scientific laws are generally viewed as *ceteris paribus* generalizations that hold only under specified conditions. This interpretation, of course, relaxes the definition considerably but at the same time makes it more practical. It is often thought that if scientists have discovered any exception-less regularities that are laws, they have solely done so at the level of fundamental physics [18]. For our purposes we could be comfortable with any of the above definitions but we will be looking for certain desiderata to make the attribution of a law to whatever it it is QM theories will present us with.

To summarize, the desirable characteristics are:

- Exceptionless generalizations, either universal or ceteris-paribus;

- Supported by counter-factuals;
- Invariant under many conditions;
- Simple; and
- Are causal in nature.

The last attribute is significant for our further discussion and is by itself often ruled to be a sufficient ingredient of an explanation. Let me elaborate.

4.2 Causation

The second group of theoreticians dealing with explanation believes that to explain something means to show how the *explanandum* was brought about. In other words, they are tracing back variations in the explanandum set–say, $Y = \{y_1, y_2, y_3, \ldots, y_N\}$ back to the original set, say $X = \{x_1, x_2, x_3, \ldots, x_N\}$. As the theory goes, if one can establish the influence, a corresponding mechanism, magnitudes of change, he or she has necessary and sufficient explanans to prove the explanandum. Critically, there is no notion of law figuring in this definition. It is not necessary for set X to be a law or any such thing. It is simply a set of initial conditions that is deemed to be at the origin of a mechanism that results in changes of set Y. Causation is arguably the most essential ingredient in Woodward's and Salmon's theories of explanation. In their view, if we can pinpoint causation, we can determine how the event was brought about, and that would be sufficient for explanation. In other words, we are phrasing causal explanations in terms of causal relations. Therefore, the question becomes about what exactly makes for a causal relation.

There is a rich historical account for the philosophical discussion on causation. Bertrand Russell framed the question in epistemic terms, that is, the ability of the observer to make inferences about events given other events. This definition came in for criticism by Wesley Salmon who concentrated on defining the 'ontic' mechanism for transmitting the causal influence in the form of a marker[28]. Causation mechanism was subsequently defined as an exchange of a signal in the form of energy or information.

Regardless of what transmission mechanism is involved, it appears that the above account establishes only the necessary condition for causation and not the full sufficient set of attributes. In Woodward's telling example of why the mechanism by itself is insufficient, consider the cue ball hit by a cue stick marked by blue chalk. The cue ball, having been set in motion by a cue stick, hits the eight ball, passing the chalk mark on to it at the same time setting the eight ball in motion in such a way that it sinks. The passing of the mark in this example establishes the causal mechanism, but it is not what made the eight ball sink. Rather, the trajectories of the balls, their masses, and the linear momenta of their relative motions were the cause of the eight ball sinking, and if we change any of the physical properties of the causal system, we could reach a different outcome. This is why Woodward requires counterfactual support for causality. In his view, this counterfactual support is solved by introducing the notion of manipulability.

Manipulability is defined through the process of intervention. In Woodwards words: "I's assuming some value $I = z(i)$, is an intervention on X with respect to Y if and only if I is an intervention variable for X with respect to Y and $I = z(i)$ is an actual cause of the value taken by X"[30]

This definition aims to account for noise in the set X that could be a contributor to the changes in the set Y in parallel to the members of the set X that are being intervened upon. Significantly, Woodward makes this definition sufficiently general to foresee possible criticism on the basis of it being anthropocentric. His manipulation does not require a human manipulator and makes no reference to the limitations of what humans can and cannot do. "An event or process not involving human action at any point will qualify as an intervention on X as long as it satisfies" the above definition[30].

In my view, Woodward's notion of causality accords itself well with the scientific realism that I espouse as it does not limit its causal coverage to the observable variables, rather it is broad enough to provide for possible inferences of unobservable variables on the basis of what we can in fact observe.

5 Wave Functions with and without Ontologies

Now that we have established the theoretical framework for what will count towards explanatory credentials in my analysis, we will proceed to putting these definition in the setting of QM.

5.1 Can wave function formalism be a law?

The logical place to start is to look at the mathematical content of QM that, let us be reminded, essentially deals with two objects - the wave function Ψ and the Hamiltonian that is a Hermitian operator and is a function of other Hermitian operators, such as those representing position, momentum, spin, etc.

Regardless of whether we establish that the wave function, which is computable but is unobservable, at least based on experiments to-date, has any ontological significance, we could explore an avenue of explanation that Hempel offers by trying to determine if the mathematical formalism of the Schrdinger equation itself can be construed as a law. Answering this last question in the affirmative could give us ground to investigate the explanatory potential of the QM theory from Hempel's deductive-nomological viewpoint.

Note that the choice of words is not a matter of semantics. The Copenhagen interpretation of QM is not about the wave functions; rather, it is about the results of experiments. Bohr and Heisenberg were not attributing any philosophical meaning to the formalism, using it for its utilitarian value only. So for the purpose of our discussion of what exactly establishes explanatory credentials for QM theories, the question of whether QM formalism (the Schrödinger equation) per se is a law or whether a wave function per se is a law is different not in nuance but as a matter of principle.

Returning to the formalism: on the surface, it is a mathematical construct that allows us to predict the empirical results of experiments. Being a tool that makes experimental predictions for the observable quantities (position, momentum, spin) with precision hitherto unseen in the history of science, should certainly enable us to categorize it as a description of a regularity of the kind for which we so far observed no exceptions.

The Hamiltonian can be viewed as a determinant of how the wave function evolves in time. But what does it mean to say the"wave function is such and such"? I take it to mean that it is the same as fixing the truth value of counterfactual claims, i.e. if the wave function were different the set of observables would change also. Well, this is the the kind of thing that laws do. Equivalently, if the particles had this configuration, this is how they would move and continue to move in a completely deterministic fashion. Once we compute, say, the discrete values of energy, an observable, based on whatever formula we derive for the wave function - this is what we end up observing, this is what we end up registering in the laboratory. On the face of it we have the full support of counterfactuals.

So by pointing out the predictive value of the Schrödinger equation, its perfect account of all observable phenomena, its support by counterfactuals - did we just make the case for it being the law? There are weighty arguments that count strongly against this.

Laws are generally time-independent and simple. Wave functions (or equivalently in mathematics of the equation in Heisenberg's formulation, Hamiltonian operators) evolve in time and are complicated. The Schrödinger equation for which the wave function is a solution is a second order partial differential equation. Being of the maximum possible empirical strength in perfectly predicting observable experimental results, it is not particularly simple or elegant, a desirable but in my view far from a necessary attribute of a law-like relation. Importantly, the wave function formulation has time dependency that adds a level of complexity. As David Albert eloquently sums it up: "It's of the very essence of what it is to be a law (after all) that laws are relatively simple and relatively a-temporal sorts of things, but wave-functions are as a general matter fantastically complicated, and complicatedly time-dependent"[1].

The lack of simplicity could make us raise a serious objection to the Schrödinger equation being put in the same camp as other formulations generally taken to be laws of nature but does not necessarily completely invalidate its law-like claim. Here is what may, in my view. The Schrödinger equation ($i\hbar\dot{\Psi} = \hat{H}\Psi$) is a formulation of mathematics that is composed of two objects: the wave function and the Hamiltonian operator. An operator is the quantum mechanical proxy for observables: position, momentum, energy, spin, etc. The values that the operators assume are real numbers at the time of measurement.

So, what mechanism within the Schrödinger equation is *responsible* for predicting future observables? Is it the *prior* observables themselves? Well, this sounds circular. It simply does not make sense to me that an observable, once measured, could be predictive of what any successive observable is going to be in and by itself. It is merely the recording of a measurement. In my view, the only thing that *guides* the future observables, is the wave function, not the observables themselves. This is a big claim, as it would require the wave function to acquire causal powers, and therefore become a *be-able*, so to speak, or to apply a technical term, to acquire an *ontology.*

To re-iterate, this is how the process works: we measure some observable, say, the position, then another observable, say, the momentum. On the basis of these measurements we compute the Hamiltonian operator for the system, and then derive the formalism for the wave function on the basis of the fact that the wave function is an eigen-function of the Hamiltonian.

So if we agree (and I do) that the observables themselves cannot be the causes of future observables we need to determine whether the wave function part of the Schrödinger equation, not the Hamiltonian, can acquire law-like characteristics. Indeed, the wave function, once computed, provides a deterministic account of all values of the Hamiltonian for posterity.

Let us see what we can take the wave function to be. First, it is a mathematical construct, an abstract object. I refer to a simple definition provided in the Stanford Encyclopedia of Philosophy that defines one of the necessary conditions for being an abstract object as its *causal inefficacy.*

Going back to our discussion about what it means to be a law, would it be possible to take a view on whether the mathematics of the wave function or a mathematical formulation of any general form *in and by itself*, can be construed as a law?

My strong personal view rooted in scientific realism is that something, anything, described in the language of mathematics needs to be describing something with an *ontological status*, something that is metaphysically a *be-able*, in order to be relevant to the discussion of cause and therefore have a chance of acquiring law-like characteristics. Whether we take Woodward's manipulationist account or any of the alternative non-epistemic accounts of cause that we discussed, unless ontologies are present, there is nothing to intervene with, nothing to pass a mark via, and nothing to exchange energies with, and therefore nothing that could give *origin* to causation in the first place.

Affording ourselves the definition of laws absent ontologies is stepping on shaky ground. If we take the view that causal relations could be supported by pure abstractions, then any mathematical theory could be categorized as being law-like provided it manages to fit its formalism to the data. The equation $2 + 2 = 4$ could not be a law unless the numbers were attributed to phenomena that have ontologies. Otherwise, if we agree that laws do not require further explanations or elaborations, we could quickly shortcut from the formalism straight to law-hood. We would instantly be able to deem something to be explanatory if, in fact, we follow Hempel's deductive-nomological account for necessary and sufficient conditions for explanation. This course of action is an intentional oversimplification but we could easily see how we could make inferences that would fit this explanation-through-lawhood route on the basis of some mathematical formalism alone, yet arrive at statements that are completely unsatisfactory.

Many a physicist struggled with the philosophical meaning of QM formalism. One of the most telling quotes was provided by Janes: *But our present QM formalism is not purely epistemological; it is a peculiar mixture describing in part realities of Nature, in part incomplete human information about Nature all scrambled up by Heisenberg and Bohr into an omelette that nobody has seen how to unscramble. Yet we think that the unscrambling is a prerequisite for any further advance in basic physical theory. For, if we cannot separate the subjective and objective aspects of the formalism, we cannot know what we are talking about; it is just that simple* [17]

If we establish the ontological status of the wave function itself, we *indeed will afford* *ourselves a necessary condition* to explore the law-like nature of the mathematical formalism in question. This endorsement, complemented by all the other features of laws that we discussed earlier could yield a theory that explains the phenomena. If we are successful in doing that, we could claim adherence to the DN account of explanation declaring QM to be a full and complete explanation of the world. Indeed, we would have concluded that we achieved what anyone could ever have hoped to achieve for a physical theory, i.e. a perfect set of predictions for experimental results on the basis of the new fundamental law of physics.

At that point referring to the theory's law-like status may not even be required in order for this newly discovered description of reality to be explanatory, for once we establish causality we could be relaxed about what account of explanation we would like to follow as we would be able to draw our inductive inferences and ensuing explanations from the causal claims themselves.

5.2 Causation Credentials of Orthodox QM

The analysis of ontologies of wave functions and other elements of QM formalism has been attempted through the theories of wave function collapse and through Bohm's dual world theory of functions and particles. It is important to note that, as a matter of historical significance, before these theories were advanced by scientists the discussion of causal influences of wave functions on the orthodox account of the theory was killed by Bohr and von Neumann before it started.

The adherents of the Copenhagen interpretation proclaimed causality incompatible with QM on the basis of uncontrollable and unpredictable uncertainty in the evolution of the system at the microscopic level [23]. Bohr himself asserted that the basic principle of QM is "irreconcilable with the very idea of causality". Indeed, as I mentioned earlier, it is impossible to define with precision the initial and final states of the system due to the quantum uncertainty principle. Even viewed statistically, it would be hard to establish a causal link if the phenomena is inherently random and only statistically predictable. In other words, from this perspective, the manipulability account of causation would be violated by the very fact that it would be impossible to fix the values in the X-set and the dependent Y-set such that the values in the X-set could be manipulated for predictable changes in outcomes of the Y-set.

Significantly, we cannot manipulate a wave function or interfere with it. Once it is computed, it is a given and no interaction by an agent of whatever kind is possible in any meaningful sense. We are talking about a theoretical impossibility in principle, of course, not about the technological limitations of intervening agents.

A side word of caution: we should not confuse our inability to interfere with the wave function with our instrumental ability to modify the observable. Surely, we can shine a laser on an electron and excite it into a higher state of energy. The electron would be then abiding by the new wave function equation that from that point on will determine its observable properties.

As a result, Woodward's interventionist account of explanation would suffer on all of these counts. The interventionist account *invalidates* the relevance of all causal claims with respect to the the wave function. In this view, the traditional orthodox account of QM, the so-called Copenhagen interpretation does not explain anything in a strict sense of the word, and is but a computation tool, however important for its utility value to physicists.

Von Neumann dedicated much of his work to the resolution of the measurement problem, trying to explain the superpositions of quantum states and match them with perfectly determinate positions of macro objects that we take to be our measurement instruments. Separating the process of measurement into a 'system', an 'apparatus', and an 'observer' is confusing enough, but the main problem lies in the fact that in my view the issue was skirted altogether. Even if the collapse is not necessitated by the sentient observer to whom Von Neumann ascribed a crucial role of the wave function 'collapser', and the collapse happens, say, through the interaction with *any* element of the environment, even if the super-position of macro objects can be proven through experiments on decoherence, it would do precious little to enable us to establish a causal influence leading to an explanation about the state of the world that the wave function describes.

As an interim summary, let us agree that any *interpretation* of QM formalism can only be taken to be an *explanation* of the state of the world if we can somehow agree that the postulates of QM are the newly discovered laws of nature. This would force us to pinpoint *causal* influences exerted by the wave function described by QM formalism. It would be a convenient view to take if we could do so *without* further elaborations on ontological status of the objects described by this formalism - and this is implicitly what the Copenhagen interpretation is telling us to do. The proliferation of theories interpreting QM in the ensuing years is a tell-tale sign that this was something that most scientists were not comfortable with.

Absent the causal influence QM would need to be complemented by additional variables, postulates, ontologically significant objects, etc. in order to explain anything.

5.3 Einstein-Podolsky-Rosen Paradox

Notably, present-day philosophers of science attribute significant attention to the discussions of causation in QM as exemplified in a so-called Einstein-Podolsky-Rosen (EPR) paradox whereby the spin states of an entangled electron/positron pair are determined through the measurement of the spin of only one particle in the entangled state. Regardless of the spatial distance between the two particles, the spin of the other entangled particle in such a pair will be thus determined. The fact that the information in these experiments seem to be passed over at super-luminal speeds supposes non-locality of quantum interactions and an associated cluster of problems related to causality. Indeed, how would a causal *mechanism* work as a matter of principle if we stick to the view that the fundamental laws of physics reduce the maximum speed of mass-less particles and therefore any interactions resulting in the passing of information between them to the speed of light.

This restriction of physics is universally accepted as a law of nature and is based on the theory of general relativity. It raises understandable doubts as to the possible existence of *any* causal mechanism, regardless of how elaborate. If we take the spin measurements to be two separate events there is not anything in nature that should allow particles in three-dimensional space to communicate with each other instantaneously. Research suggests some convenient philosophical interpretations: X (measurement on the first particle) and Y (measurement on the second particle) are not distinct events; or an alternative suggestion that "they are separate events and are not probabilistically dependent on one another in virtue of being a cause and effect or effects of a common cause bearing non accidental but a non-causal relation to one another [12]."

Although the EPR paradox provides a rich field of research and is worth mentioning simply because any book on QM causality brings it to the fore alongside elaborations of causality of Newtonian gravitation we are not concerned in this paper with solving the problem of non-locality and, more to the point, provide a detailed account of the *mechanism* for causality (because it is the mechanism that is in question by the non-locality issue, not the outcome). Granted, we seem to be having a genuine problem of physics in that the quantum wave seems to be propagating at super-luminal speeds. However, I am assuming that the solution to the problem of the mechanism is secondary to the issue of whether the causal influence can have an *origin* in the first place. And this latter issue is what this paper takes to be its central topic.

Therefore, let us go back to the wave function and see whether it could be something more than a mathematical denotation. Let's see if there is anything again that can make it more law-like through an interpretation that is different from the orthodox one. The relevant investigation tactic could be to establish exactly how it predicts the results of experiments.

5.4 Ontologies: Bohmian and GRW Interpretations

Right from the outset and in parallel with the Copenhagen interpretation, quantum research was characterized by the quest for ontologies. In the 1950's David Bohm, a British mathematician, developed a renewed version of de Broglie's original, pilot wave theory, now known as Bohmian mechanics. The theory was pioneered by de Broglie as early as 1926 when he made the original articulation of his concept at a conference. De Broglie eventually gave up on his own theory and was pushed by Heisenberg into accepting the orthodox interpretation of QM with David Bohm picking up the pieces three decades hence. For various reasons, some of them having to do with politics, de Broglie-Bohm interpretation was not getting the hearing it deserved until the last decade when the theory was cast into the spotlight for the third time since its inception.

Another runner-up for the theory dealing with ontological significance of the wave functions was developed in the middle of the 1980's by Ghirardi, Rimini and Weber and became known simply as the GRW. The theory underwent modifications in the subsequent years, so we are endowed with the original theory, a so-called GRWm and its updated version, GRWf.

Bohmian and GRW accounts were historically pitted against each other and presented as dichotomous [25]. Indeed, in GRW theory the wave function describes the system completely with the function being given by a deterministic Schrödinger equation before it undergoes the so-called collapse, where the Bohmian account introduces a hidden variable of ontologically significant particles *in addition* to the wave function.

However, (and my view in full accordance with that of Sheldon Goldstein [9]) both of these theories: "are ultimately not about wave functions but about 'matter' moving in space, represented by either particle trajectories, fields on space-time, or a discrete set of space-time points. The role of the wave function then is to govern the motion of the matter."

The sketch of these theories follows.

5.4.1 GRW

The original GRW postulates that wave functions evolve according to the Schrödinger equation until at random times they undergo spontaneous collapses, a stochastic jump process in Hilbert space. The theory supplements the mathematics by introducing a so-called collapse operator to the Schrödinger equation. The specific mathematical notation of this operator and mathematical fine tuning that needed to be introduced in order to accord the original version of the theory with the law of conservation of energy is not relevant to this paper. Suffice it to say that GRW introduced a *new constant of nature*, sigma, on the order of 10^{-7}m and specified the rates of these collapses, which are in the order of magnitude of millions of years per single collapse event for an individual particle. In other words, the evolution of the wave function is in accordance with the Schrödinger equation but is interrupted by collapses.

How does this theory morph into what is our everyday macro experience? If the frequency for these collapses, according to the theory, is extremely rare for each particle, how indeed do we make our macro objects to have definitive spatio-temporal positions? The answer is simple, in that macro-objects consist of trillions of wave functions with some of them undergoing collapses with a resultant definitive state of observables.

Gian Carlo Ghirardi, supported by Sheldon Goldstein believes that the theory specifies so-called primitive ontologies, either in the form of a *matter density* ontology (GRWm) or a *flash* ontology (GRWf). These variables are determined by the wave function and are therefore not hidden (unlike in the Bohmian account), so the wave function with the introduction of a collapse operator completely and accurately accounts for the state of the universe and is ontologically significant[8].

5.4.2 Bohmian Mechanics

According to the Bohmian view, universe consists of two types of objects: wave functions that live in configuration Hilbert space and particles that exist in three-dimensional space. These particles do have *definite positions and momenta* at all times and *continuous trajectories* and the trajectories are determined determined by a 'velocity field' in accordance with the so-called guidance principle, mathematically articulated. The 'velocity field' is determined by what is called 'the probability current' that depends upon the state vector of the system in accordance with the classic rule for determining probabilities in QM.

It is a consequence of the Bohm theory that these initial positions and momenta of the particles are in principle impossible to determine; all that we know about these initial positions is that they are distributed in such a way that the probability that any one of these particles is at any given place at $t = 0$ is the standard quantum mechanical probability (and similarly for the momentum distribution). That quantum mechanical probability distribution is then preserved through all time. In this way, the Bohm interpretation explains why the probability of finding any given particle in any given place or of finding the whole system of particles in any given position configuration at any given time, is in accordance with standard quantum mechanical calculations given by Von Neumann.

There are a number of notable objections to the theory, specifically to the geometry it implies[1]. This objection targets the two-space interpretation, namely the configuration space for wave functions and 3D space for particles, as incoherent for the purpose of the guidance principle to be valid, as the geometrical relationship between the two can not hold. However the adherents to the theory do not view this and other objections as insurmountable.

David Albert himself provides a radical interpretation of the theory by specifying a particular type of a Hamiltonian that 'enacts' particles in a 3D space and makes our experience of macro objects possible. On this theory, the perceivable three-dimensional universe is a projection of a co-called 'marvelous' point, a position of possibly just one particle and one wave function in the entire universe on to a $3m$-dimensional subspace. For example, a chair is a projection on to a particular $3q$-dimensional subspace. If the projections are right, the causal relations will be the same as perceived on a macro level. On this account the laws of motion generate appearances, and geometrical appearances being no exception. If the Hamiltonian of a single particle is specified in a particular way, it would explain all appearances on a macro level.

Regardless of further technicalities and interpretation of the theory, the most significant mention is that wave functions are ontologically on par with particles. They are ontologically separate from particles and are viewed similarly to fields in a sense articulated by Maxwell for electric fields. The difference is that electric fields are caused by charged particles, so there is a dependent iterative relationship between charged particles and electric fields, whereas wave functions have a more separable ontological status. Further, configuration space in which functions exist does not make sense without the particles, and in this sense there is an ontological link between the two.

Once we have ontologies, and Bohm's theory seems to be all about validating them, we have our desiderata for causal claims that enable us to establish the theory as truly explanatory.

6 Conclusions: How Do QM Theories Explain?

A profoundly important debate is taking place among the philosophers of QM: the mainstream group to which I belong argues that causality is a necessary condition for explanation and therefore is essential for QM to be taken as a true and complete theory about the state of the world. The causal relation may be of a strong and general nature, it may be defined through the mechanics of Woodwards manipulations or be taken as such by other definitions.

The opinions on what part of QM formalism is descriptive of causality divide. There are adherents to the view that the Hamiltonian can be construed as the law of nature in and by itself and the wave function is the statistical computational tool, and yet the others believes that in order for QM to be explanatory, the wave functions need to have ontological status. I subscribe to this latter view. Even though I tried to have a look at this problem from a philosophical angle, this account of things seems to be gaining a wider acceptance among the physicists. At the time of the writing of this paper, an important submission got filed by the group of scientists at the Imperial College London who are trying to prove just this point mathematically [24].

The wave function endowed with the attribute of an ontology would be in a position to be viewed as being capable of causal influence. Established support by counterfactuals on the basis of experimental data for the observables would qualify the wave function for being a law of nature. Thus defined, the Schrödinger equation becomes a mathematical generalization of such a law. The very fact of establishing causality suffices the condition for this mathematical statement to be an explanation.

The followers of Heisenberg and Bohr take a view that QM is not and should not be rooted in causality and that *empirical observations alone* should be allowed as *principles of* *inference* without having to establish what the causal mechanism is. In my opinion, this group would like to establish law-like nature of generalizations *sans* causal influences. This approach, if followed, could qualify their interpretation of QM for Hempel's DN account of explanation (the phenomena has been reduced to a law after all, in their view). I believe however that awarding law-like status on generalizations without identifying causal influences, regardless of how useful computationally, would lead to error.

And yet the third group, the group to which many practicing physicists of QM belong based on my interviews with them, take themselves to be the supporters of the Copenhagen interpretation attesting that QM is not about the reality, is not about the state of the world but is about the measurements of a Hamiltonian: energy, position, momentum, and other observables. The theory on their view makes perfect predictions that never faulted us, and thats that. The Copenhagen camp holds that their approach has the highest fecundity value in advancing the science of physics per se and to that extent should be accepted as a guiding theory severing all future debate.

The judgment of who is right may come in one of two ways: either the result of some astonishingly advanced experiment will repeatedly and conclusively prove one of the camps right. More likely, as often happens in physics, it is the 'next big thing' coming in the form of quantum computing or another application that will prove critically useful to practitioners that will be able to sway the pendulum of opinion in one or the other direction. In the meantime, philosophers of science will entertain themselves with ever more astonishing revelations on the subject.

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