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QUANTUM INTERPRETATIONS AND SCIENTIFIC EXPLANATION IN PARADIGMATIC QUANTUM EXPERIMENTS

Abstract

In this paper, I discuss two different formalisms of quantum mechanics, i.e. the orthodox and the de Broglie–Bohm formalisms, as explanations of the interference pattern observed in the double-slit experiment. I evaluate the explanations provided by these two formalisms on the basis of Hempel's DN model of scientific explanation, showing that both formalisms can sufficiently explain the phenomenon. However, once the interpretations associated with the two formalisms come into play, the sufficiency of the DN model's evaluation of the explanations becomes questionable. Whereas the Copenhagen interpretation, associated with the orthodox quantum formalism, would evaluate the DN model as sufficient, Bohm's interpretation, associated with the de Broglie–Bohm formalism, would not. Bohm's interpretation would require descriptions containing relevant metaphysical relations to be included in the explanans. The DN model does not contain such a requirement. Then, Strevens's kairetic account of explanation will be introduced as an alternative model of scientific explanation. The kairetic account allows for descriptions of relevant metaphysical relations to be included in the explanans. I argue that the proponents of both interpretations will accept the evaluation provided by Strevens's kairetic account as sufficient. This highlights the role of quantum interpretations in modeling scientific explanation of quantum phenomena in two ways: (1) in determining the relevant explanans of the model of explanation, and (2) in evaluating models of explanation by virtue of evaluating the relevancy of their explanans or by evaluating whether the requirements of a model are fulfilled in the context of an interpretation.

Keywords: scientific explanation, quantum interpretation, the double-slit experiment, the DN model of explanation, the kairetic account of explanation

Paradigmatic quantum experiments reveal the strange non-classical features of quantum phenomena. Among paradigmatic quantum experiments, the double-slit experiment has been the center of attention for physicists and

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philosophers for decades. The Stern–Gerlach experiment, various experiments in quantum interferometry, the beam-splitter experiment, and other experiments with half-silvered mirrors, as well as experiments of the EPR type (Plotnitsky 2010: 46) also count as paradigmatic quantum experiments. On the basis of such experiments, different formalisms and interpretations of quantum mechanics can be evaluated in terms of their relative success in explaining the phenomena.

It is natural for a philosopher of physics to incorporate a quantum interpretation into the explanation of a quantum phenomenon in a paradigmatic quantum experiment. It is also tempting to think of quantum interpretations as playing a key role in the *evaluation* of explanations of quantum phenomena in a more general context of philosophy of explanation. However, that is not the case. In this paper, I try to shed light on the role of quantum interpretations in two models that evaluate scientific explanations of quantum phenomena.[1] The idea can be generalized and applied to all models and all quantum interpretations.

The goal of this paper is to show that quantum interpretations play two key roles in models of scientific explanation of quantum phenomena: (1) in determining the relevant explanans of the model of explanation, and (2) in evaluating models of explanation by virtue of evaluating the relevancy of their explanans or by evaluating whether the requirements of a model are fulfilled in the context of an interpretation. Any successful model of explanation, then, should consider such a role for quantum interpretations in evaluating an explanation of a quantum phenomenon.

I will start by evaluating the explanations of the appearance of an interference pattern in the double-slit experiment provided by two formalisms of quantum mechanics. The two formalisms are the orthodox formalism of quantum mechanics and the de Broglie–Bohm second-order formalism.[2] The

[1] By saying this, I am not claiming that I am the first to address the notion of "quantum interpretation" in the philosophy of explanation. Many distinguished philosophers, such as Woodward (2003) and Salmon (1984, 2006), have offered extensive discussions of the role of quantum interpretation in scientific explanation. My claim rather is that, in the logical structure of the DN model-based scientific explanations, no room is left for quantum interpretations as a presupposition determining their explanantia.

[2] By "de Broglie–Bohm second-order formalism" I simply refer to the formalism originally developed by Bohm in terms of the notion of quantum potential. In this formalism, the second-order (Newtonian) concepts of acceleration and force, work and energy play a fundamental role. Particles move under the influence of forces, among which is a force arising from a "quantum potential" (Goldstein 2013). Later, Dürr, Goldstein, and Zanghì (1992) presented a version of the formalism as the "first-order theory, in which it is the velocity, the rate of change of position, that is fundamental" (Goldstein 2013).

evaluation will be performed in terms of Hempel's DN model of scientific explanation.[3] Then, by evaluating the DN model's evaluation *from the point of view of two interpretations associated with the above two formalisms*, I will examine the relevance of the explanans.

The DN model holds that the metaphysical underpinnings of a scientific explanation should either be avoided or, at best, not be taken as fundamental. What is fundamental for the DN model is subsumption under a law. In the case of the double-slit experiment, the law is the "quantum superposition principle", according to which any two or more quantum states can be added together, yielding another valid quantum state or, conversely, any quantum state can be represented as a sum of two or more other distinct states. The principle mathematically appeals to a property of solutions to the Schrödinger equation: Since the equation is linear, any linear combination of solutions will also be a solution to the Schrödinger equation.

I show that an advocate of Bohr's post-EPR version of the Copenhagen interpretation,[4] associated with the orthodox formalism of quantum mechanics, would accept as sufficient the DN model's evaluation of the explanation, provided on the basis of the orthodox formalism. However, an advocate of Bohm's interpretation of quantum mechanics, associated with the de Broglie–Bohm second-order formalism, would not be satisfied with such an evaluation, and would demand that ontological ingredients be added to the explanans.

I then introduce Strevens's (2004, 2011) kairetic account of scientific explanation and argue that, once the role of quantum interpretations in this account is acknowledged, the proponents of both interpretations will assess Strevens's kairetic account as a sufficient model of explanation. The reason is that, contrary to the DN model, the kairetic account allows for the relevant metaphysical relations to be included in the explanans. This makes it possible for the proponent of Bohm's interpretation to accept as sufficient the kairetic account's evaluation of the explanation of the appearance of the interference pattern in the double-slit experiment. However, the role of quantum interpretations in quantum theory is either ignored or insufficiently clarified by the kairetic account.[5] In this paper, I will highlight it.

[3] In this paper, I take models of scientific explanation to *explain* or *evaluate* (or model) explanations of phenomena, i.e. to explain why explanations of phenomena are explanatory.

[4] The Copenhagen interpretation is not a unified idea. Even Bohr's version of the Copenhagen interpretation underwent significant changes over time. This is why I use Bohr's post-EPR version of the Copenhagen interpretation. A list of the characteristic features of Bohr's post-EPR version of the Copenhagen interpretation comparing those features with the characteristic features of pragmatism and logical positivism can be found in (Maleeh 2015a) and (Maleeh, Amani 2013).

[5] Strevens (2011) refined his account of scientific explanation by adding to it new con-

The goal of this paper will not be achieved unless a detailed account is given of what a quantum interpretation is. Such an account, as we will see, makes it possible for a quantum interpretation to legitimately play the aforementioned roles in models of scientific explanation.

By "an interpretation of quantum mechanics", I refer to a set of statements that attempt to explain quantum mechanics. A quantum interpretation provides a conceptual or argumentative framework to understand and *account for* those aspects of quantum mechanics that violate some fundamental principles of classical physics. Such a framework aims to relate to one another three elements associated with quantum mechanics. First, the mathematical formalism of quantum mechanics, which deals with mathematical objects such as wave functions, the Schrödinger equation, state vectors, etc. Whether such mathematical objects refer to any corresponding reality or only serve as instruments for prediction and control is determined by quantum interpretations. Second, the experimental facts of quantum physics, which have to do with the experimental setup of the performance of a well-defined measurement in the presence of a well-defined measuring instrument in the process of observation. "Observation" itself covers the observed phenomenon as well. Again, whether or not a special role is attributed to "measurement" is determined by a quantum interpretation. And, third, the physical meaning of the mathematical entities of the formalism and the experimental setup.

In this paper, I take quantum theory to include both a formalism and its corresponding interpretation.

Note that, although quantum interpretations are not theories of explanation, they can evaluate models of explanation in virtue of the relevancy of the explanans in the context of an adopted quantum interpretation. To put this another way, an interpretation can evaluate a model by assessing whether or not the requirements of the model are fulfilled in the context of an adopted interpretation. This will be elaborated in sections 2 and 4.

Simplicity of exposition has not been my only reason for choosing the DN model and the kairetic account as two models of explanation of phenomena in the double-slit experiment. The DN model is a classical model that represents those accounts of scientific explanation that emphasize the epistemological aspects of explanation. In this model, metaphysical relations are replaced by logical relations such as entailment. More importantly, as Salmon (2006: xiii) has put it, "almost everything written on the nature of scientific explanation in the last thirty-odd years derives directly or indirectly from that

cepts, such as "elongation", "intensification", "deepening", "frame-working", and "black-boxing". The addition of such concepts, however, cannot invalidate my argument regarding the vagueness of the role of quantum interpretations in the kairetic account.

[Hempel, Oppenheim 1948] essay", in which the DN model was first introduced.

The kairetic account represents those accounts of scientific explanation that modify the original DN model by infusing it with metaphysical relations by means of unified modern theories. By choosing the DN model and the kairetic account, then, I cover a wide range of accounts (models) of scientific explanation. This can also provide grounds for generalizing the idea that one cannot evaluate an explanation of quantum phenomena without presupposing a quantum interpretation.

Similarly, I have chosen two interpretations of quantum mechanics that cover a wide range of quantum interpretations. The Copenhagen interpretation represents those epistemic non-causal indeterministic interpretations that are concerned with our *knowledge* of reality and emphasize the role of measurement. By contrast, the Bohmian interpretation can be a representative of ontic interpretations that have primarily *causal* concerns in explanation. According to such interpretations, physical explanations need to appeal to metaphysical properties and relations.

One should bear in mind that the argument presented here, which emphasizes the significance of quantum interpretations in models of scientific explanation of quantum phenomena, can be generalized to all quantum theories.

1. THE DOUBLE-SLIT EXPERIMENT

1.1. BACKGROUND AND IMPORTANCE

The importance of the double-slit experiment lies, among other things, in the *clarity* with which it reveals the central difficulties of quantum mechanics that can only be addressed by the nonclassical epistemology of quantum phenomena and quantum mechanics. These difficulties will be dealt with in section 1.2.

One of the advantages of the experiment is that it can be conducted with all quantum objects, including those that are much larger than electrons and photons.[6] Another advantage is that, more than any other quantum experiment, it can be explained *qualitatively* without an appeal to technical knowl-

[6] The largest entities with which the double-slit experiment has been conducted were molecules comprising 810 atoms with total mass over 10000 atomic mass units (Eibenberger et al. 2013).

edge of quantum theory, although any accurate *quantitative* prediction of the associated outcome requires the mathematical formalism of some quantum theory. Finally, as Plotnitsky has noted, the experiment

> manifests especially dramatically the key probabilistic and statistical aspects of our predictions concerning quantum phenomena — in particular, the relationships between randomness and probability and hence between randomness and certain (correlational) order, which the probabilistic predictions of quantum mechanics capture. (Plotnitsky 2010: 47)

Before the 1960s, when the double-slit experiment was actually preformed as a quantum experiment, it functioned as a thought experiment, although there had been hardly any doubt that it could in principle be conducted on any type of quantum objects.

When it was performed as a classical experiment with light, the interference patterns found in Young's double-slit experiment in 1801 undermined Newton's corpuscular theory and appeared to have answered the question of the nature of light in favor of the wave theory. This remained a dominant view before further development of quantum theory, mostly through Planck's discovery of black body radiation law and Einstein's explanation of the results of the photoelectric effect proposing that a beam of light is not a wave propagating through space but a collection of discrete wave packets (photons). This led Louis de Broglie to hypothesize that all other elementary constituents of matter, such as electrons, eventually show the same dual character. The hypothesis was soon experimentally demonstrated in the 1920s.

In the 1960s, Claus Jönsson (1961) conducted the double-slit experiment with electrons. Then Pier Giorgio Merli, Missiroli, and Pozzi (1976) performed the experiment with "one electron at a time" (single-particle version of the experiment) in 1974. Jönsson's experiment was voted the most beautiful experiment ever performed in a 2002 poll conducted in *Physics World* (September 1, 2002).

The double-slit experiment played a crucial role in Bohr's thinking about quantum phenomena and quantum mechanics, especially during his exchanges with Einstein. The main reason for Bohr's insistent appeal to the experiment was that it could effectively test predictions about quantum phenomena and quantum mechanics by comparing these predictions with the numerical data found and quantum phenomena observed in the double-slit experiment. Predictions that are not confirmed by experimental data may then be rejected.

In what follows, after a brief description of the experimental arrangement of the experiment, I will address some questions posed by the double-slit experiment. These questions can only be tackled by the nonclassical epistemology of quantum phenomena and quantum mechanics.

1.2. THE EXPERIMENTAL SETUP

The setup of the double-slit experiment[7] is composed of a monochromatic light source, which also makes it possible for photons to be emitted one by one (Fig. 1). A diaphragm with a single slit (A) is placed at some distance from the source. A second diaphragm with two widely separated slits (B) and (C) is put at a sufficient distance from the first diaphragm. The arrangement will be completed by adding a silver bromide photographic screen at a sufficient distance from the second diaphragm. Two setups are provided, in each of which the source emits a sufficient number of quantum objects (photons) permitted to pass through the slits, hitting the photographic screen where the traces of the collisions are recorded.

The second setup differs from the first in that it involves some devices, such as counters, attached to it. This allows us to know which slit each particle passes through. Such devices are called "which-path" or "which-way" devices. Note that the traces seen on the photographic screen are the *effects* of the processes that involve a certain type of physical objects (more specifically, quantum objects). We *infer* the existence of quantum objects from the traces or marks they leave on the screen while colliding with it. In both setups, each collision of quantum objects with the screen leaves a mark similar in appearance to a very small object, idealized as a particle in classical physics. So, in both setups, *individual* quantum phenomena may correspond to the particle-*like* behavior of quantum objects. However, this does not mean that quantum objects are particles in the sense of classical physics.

In the first setup, the traces of collisions between the quantum objects and the screen collectively leave a wave-like interference pattern (Fig. 1A).[8] The appearance of the interference pattern itself is in principle independent of the distance between the slits or the time interval between the emissions. There can be one quantum object at a time emitted toward the slits with an arbitrarily long interval for each emission, so that each emission takes place after the collision of the previously emitted object took place. This makes the double-slit experiment even more mysterious: quantum objects manifest both wave-like *and* particle-like behavior. In each run of the experiment, the

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[7] The description has been adopted from Plotnitsky (2010: 48-52).

[8] I use "interference pattern", "wave-like pattern", "wave-like phenomena", and "showing wave-like behavior" interchangeably.

observed individual behavior is particle-like although collectively quantum objects form an interference pattern. In other words, the interference pattern emerges out of multiple individual events.

However, in the second setup, the one with which-way devices attached, the interference pattern never appears on the photographic screen (Fig. 1B). Quantum objects show particle-like behavior[9] both individually and collectively as if the experiment were conducted with classical objects. In the second setup, quantum objects appear to be "aware" of the presence of the counter and are able to "choose" where to land on the screen accordingly.

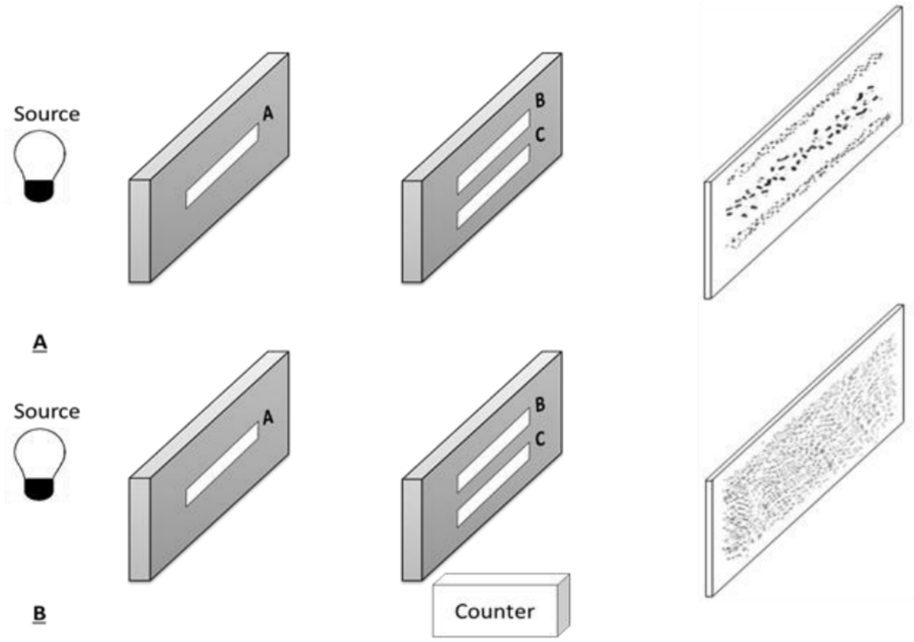

Figure 1. The Double-Slit Experiment

The weird behavior manifested in the above experiments is sometimes referred to as the quantum measurement paradox. This paradox, together with the mathematical formalism of quantum mechanics, cries out for an interpretation.

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[9] I will use "particle-like pattern", "particle-like phenomena", and "showing particle-like behavior" interchangeably.

1.3. TWO RIVAL INTERPRETATIONS

In this section, I review two rival interpretations of quantum mechanics as applied to the double-slit experiment: Bohr's post-EPR version of the Copenhagen interpretation of the orthodox quantum formalism (hereafter "the CI") and Bohm's interpretation of the de Broglie–Bohm second-order formalism of quantum mechanics (hereafter "BI").

As regards the double-slit experiment, the CI is virtually synonymous with Bohr's notion of "complementarity" (Bohr 1928). The post-EPR Bohr considers Heisenberg's "uncertainty principle" as reflecting the ontological consequence of Bohr's claim that kinematic and dynamic variables are ill-defined unless they refer to an experimental outcome (Faye 2014). This made the later Bohr use the concept of "phenomena" or "information" as being complementary, not "descriptions" that attribute kinematic and dynamic properties to atoms, as he had maintained earlier. By using the notion of phenomena in complementarity, Bohr[10] emphasizes "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 1949: 39-40, emphasis in the original).

In the context of the double-slit experiment, this requires that quantum objects become waves *or* particles after the performance of a well-defined measurement in the presence of a well-defined measuring instrument. In other words, nothing can be said about the nature of quantum objects apart from their phenomenological appearance. Ultimately, any description (and consequently any physical explanation) attributing any property to any quantum objects and their behavior before, during, or after the act of measurement has taken place is *in principle excluded*. The Copenhagen interpretation rejects any meaningful "interpretation" beyond a mere instrumentalistic description.

An alternative to the above interpretation is BI, associated with the de Broglie–Bohm formalism with a commitment to the notion of quantum potential. In what follows, the key features of the non-relativistic version of the formalism and its interpretation are briefly outlined.

Unlike the orthodox formalism of quantum mechanics, which describes a physical system in terms of the wave-function (ψ), a physical system in Bohmian mechanics must be described by a wave-function *and* a configura-

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[10] Following John Honner (1987) and Arkady Plotnitsky (2006, 2010, 2012), I take Bohr's mature notion of phenomena to be the effects of the interactions between quantum objects and measuring instruments that classically manifest in measuring instruments (Plotnitsky 2012: 138).

tion, *viz.*, the position of the corresponding quantum objects (de Broglie 1927, Bohm 1952). The wave-function in this account also satisfies the Schrödinger equation.

Particle velocities in Bohmian mechanics are given by the "guidance equation". The equation equips particles with a dynamic that depends on the wave-function. Metaphorically, quantum particles are guided by the ψ-field, moving along continuous trajectories and having a well-defined position at every instant.[11]

The position-distribution, ρ, of an ensemble of systems in Bohmian mechanics is described by the wave-function through the postulate $\rho = |\psi|^2$, called the quantum equilibrium hypothesis. The postulate ensures the reproduction of all predictions of the formalism of the orthodox quantum mechanics. It also guarantees that the theory does not experimentally violate Heisenberg's uncertainty principle (Dürr, Goldstein, Zanghì 1992).

Passon (2006) lists the key characteristics of BI associated with the de Broglie–Bohm theory as: determinism, dispensability of complementarity, non-locality, and attribution of no special role to measurement. Determinism in BI refers to the thesis that the evolution of the system is uniquely fixed at any given time by the wave-function and the configuration of the system. However, compared to the formalism of the orthodox quantum mechanics, such determinism does not contribute more predictive power to Bohmian mechanics, which is to say all predictions of the theory remain probabilistic. But, unlike the orthodox quantum mechanics, the latter randomness arises from averaging over ignorance. As is seen, the notion of determinism in BI is different from what had been tacitly identified with the CI, i.e. exact predictability and controllability (Bohm, Hiley 1993: 19).

Note that, for Bohm, the question of determinism is not fundamental. For instance, in 1954, Bohm and Vigier developed a model with a stochastic background. Indeed, the reason for proposing BI as an alternative to the CI does not root in the indeterministic standpoint of the CI but in the vague way it deals with the measurement problem. Therefore, unlike the CI, BI is primarily concerned with ontology, or with that which is (Bohm, Hiley, Kaloyerou 1987, Bohm, Hiley 1993: 2).

In Bohmian mechanics, explanations of many phenomena, including the appearance of the interference pattern in the double-slit, require both wave *and* particle aspects of the quantum particle to be simultaneously taken into account. In this theory, matter is described both by wave-like (the wave-function)

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[11] Berndl et al. (1995) proved the global existence of the Bohmian trajectories. The proof was later extended by Teufel and Tumulka (2005).

and particle-like (the position) quantities. Therefore, in BI, the notion of complementarity is dispensable.

In an *N*-particle system, the guidance equation simultaneously links the motion of every particle to the position of other particles. This ability of the particles to influence each other over arbitrary distances is what is meant by "non-locality" in Bohmian mechanics.

Finally, by introducing the notion of "quantum potential", Bohm maintains that particles move along the Bohmian trajectories under the action of a novel "quantum force" which, in the double-slit experiment, affects every quantum particle, making it follow a particular path and go through one of the slits leaving an individual spot on the photographic screen. The spots collectively form an interference pattern (Bohm, Hiley, Kaloyerou 1987). With the experiment thus construed, no special role can (and should) be attributed to the act of measurement.

Apparently, in contrast to the CI, which counts any attribution of any property to the quantum objects as meaningless and prohibits describing processes and mechanisms before the act of measurement, BI provides a full metaphysical (i.e., causal-ontological) account of the appearance of the fringe-like patterns in the double-slit experiment. In fact, as we move from the CI to BI, explanations become metaphysically richer (Maleeh 2015b). As opposed to the CI, which is primarily directed towards epistemology, BI is primarily concerned with ontology and treats the question of how we obtain knowledge as a secondary one (Maleeh 2014: 459-60).

To recapitulate, what distinguishes the above interpretations from one another is the significance and priority they attribute to ontology versus epistemology. The significance and priority of ontology increase as we move from the CI to BI. Adding or removing ontological ingredients may also turn one theory into another. For example, by adding the metaphysical postulate that position measurement is always dynamically significant, Hans Halvorson and Rob Clifton (1999, 2002) argued that Bohmian mechanics can be obtained from Bohr's complementarity.

As we will see, what is central here is not which interpretation a physicist presupposes or why she chooses this interpretation rather than another, but that a quantum interpretation is always an important element of a physicist's explanation of paradigmatic quantum experiments. Whether the physicist chooses the orthodox formulation or the de Broglie–Bohm formulation in formalizing the double-slit experiment, the philosopher of physics would *naturally* appeal to a corresponding interpretation, *viz.* the CI or BI respectively, to scientifically explain the phenomena in such an experiment.

To sufficiently model explanations in paradigmatic quantum experiments in the realm of philosophy of explanation, I claim it is also necessary to include a quantum interpretation as discussed in the next sections.

2. HEMPEL'S DN MODEL AND THE EXPLANATION OF THE DOUBLE-SLIT EXPERIMENT

2.1. BACKGROUND

Hempel and Oppenheim's (1948) model of explanation has a number of interesting features. First, on the DN model, an explanation has to have the structure of a logical argument, with laws among its indispensable premises. This is the first formal requirement for an explanation of an event. The second feature is a commitment to objectivity in science and the rejection of any appeal to subjective feelings, *interpretations*, and judgments. The third feature is a commitment to the syntactic analysis of language as the proper method of philosophy. Kim (1999: 3) calls this feature syntacticalism.

In the DN model, metaphysical relations are replaced by logical relations. According to this model, "the explanandum must be a logical consequence of the explanans", which must contain general laws. "Since the explanandum is assumed to describe some empirical phenomenon", the logical deducibility of the explanandum from the explanans entails that the explanans must have empirical content being capable, at least in principle, of being tested by experiment or observation (Hempel, Oppenheim 1948: 137). The latter also echoes objectivity as a property of scientific inquiry.

Here, the term "objectivity" has the weak sense embraced by the orthodox logical empiricists. In explanations in physical sciences, objectivity in this sense does not require any privileged access to truth,[12] depending, instead, on intersubjective reliability: when faced by a specified experimental setup, scientists can unambiguously agree on what can and what cannot happen (Lindley 1996: 159-160).

As regards the third feature, the early Hempel held that all concepts needed to do science are purely syntactic (syntacticalism). Science is a system of statements that are of one kind and are never compared with a "reality", with "facts" (Hempel 1935: 51). For Hempel, the treacherous land of metaphysics lies beyond language. However, in the DN model, one of Hempel's conditions is the requirement that the statements comprising the explanans

[12] Therefore, the idea is in line with the coherence theory of truth.

must be true. This brings semantics into play, which in turn represents metaphysics. However, by switching their explicandum from the statement "(*T*, *C*) is an explanans for *E*"[13] to "(*T*, *C*) is a *potential* explanans for *E*", Hempel and Oppenheim (1948: part III) managed to avoid even minimal semantic involvement (Kim 1999: 6).

Syntacticalism is directly linked with the second and third formal requirements for a DN explanation of an event — i.e., the requirements that at least one of the premises of the argument must be a law of nature and that the premises of the argument must be true. The third requirement stems directly from Hempel's positivist theory of truth. Hempel's theory of truth goes against the correspondence theory of truth, according to which propositions or sentences can be compared with facts. In Hempel's syntacticalism:

> causation and causal explanation remain out of the picture as far as the official story [of explanation] is concerned. There is no requirement that the singular sentences of the explanans "specify" or "describe" events or conditions temporally antecedent to the event specified by the explanandum, or that the explanatory laws be, in some sense, "causal laws" (and not, for example, regularities between collateral effects of a single cause process). There is not even the requirement that the singular sentences of the explanans be "event describing" — that is, that they be sentences of the sort that can specify the occurrence of events. Actually, Hempel explicitly refuses to require, for explanations of individual events, that the explanans include any singular sentences at all, on the ground that it is possible to formulate a singular explanation by universally instantiating a law. Here Hempel appears to be thinking that the following would be a perfectly good singular explanation:
> Every *F* is *G*.
> Therefore, if *a* is an *F*, *a* is *G*. (Kim 1999: 8-9)

This, for example, requires the exclusion of any statement that refers to Bohm's beables from the explanans of the DN argument[14], as we will see in sections 3.2 and 5. The kairetic account, however, does not have such limitations.

As shown above, the key features of Hempel's philosophy of explanation are backed up by the idea that metaphysical underpinnings of scientific explanation should be avoided or, at least, should not be taken as primitive and fundamental. Hempel's notion of explanation is *epistemological*, not onto-

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[13] Here, *T* and *C* stand for a theory (i.e., a set of laws) and a set of singular premises describing antecedent conditions respectively. *E* stands for the statement of the event to be explained.

[14] "Beable" is the term John Stewart Bell (1975, 2004) devised to refer to those elements of a theory which are "to be taken seriously, as corresponding to something real" (Bell 2004: 234). He suggested the term as a replacement of the traditional term *observable* in quantum mechanics. The term "beable" is aimed to conceptually distinguish the being of quantum systems from whatever it means to observe them.

logical. That is, the standard for a good explanation is met by good epistemological rules, not by some unreachable reality.

2.2. THE DN MODEL AND THE DOUBLE-SLIT EXPERIMENT

The emphasis that the DN model puts on avoiding metaphysics and on the priority and significance of epistemology brings it much closer to the CI than to BI and, in modeling scientific explanation of quantum phenomena, the DN model shares more philosophical elements with the CI than BI.

In particular, the second and third features of Hempel's DN model stated above are in perfect harmony with Bohr's mature philosophy, especially when it comes to the notions of reality, objectivity, and instrumentalism. According to Bohr, the world exists independently of our minds. However, for him, truth is an epistemic notion on the grounds that it is related to our cognitive abilities (Dummett 1982).

Thus, in Bohr's eyes, while the world exists independently of us, physical reality detached from human perceptual capacities is ungraspable. The existence of such an objective real world makes intersubjective communication possible. According to Bohr, the experiential statements of classical mechanics are true if they *can* be verified. However, the experiential statements of quantum mechanics will be true *only* if they are *actually* verified through a registered observation (Maleeh 2015a). The classical manifestation of the interactions between quantum objects and measuring instruments, as phenomena, then, ensures the verifiability or falsifiability (objectivity) of our theory. This also ensures the unambiguous communicability of our experimental statements. In this context, "objective" means *intersubjectively valid*. Thus, like Hempel, Bohr accepts a weak form of objectivity and realism.

Bohr's instrumentalism is also in harmony with Hempel's syntacticalism. Bohr is a non-realist as to the applicability of any theory of pure mathematics to the real physical world. For him, the value of mathematical theory is primarily instrumental.

Similarly, the mathematical formalism of quantum mechanics would not give us any "pictorial" representation of the world. It is simply a tool to probabilistically predict the outcomes of experiments:

> The entire formalism is to be considered as a tool for deriving predictions of definite or statistical character, as regards information obtainable under experimental conditions described in classical terms and specified by means of parameters entering into the algebraic or differential equations of which the matrices or the wave-functions, respectively, are solutions. These symbols themselves, as is indicated already by the use of imaginary numbers, are not susceptible to pictorial interpretation; and even derived

real functions like densities and currents are only to be regarded as expressing the probabilities for the occurrence of individual events observable under well-defined experimental conditions. (Bohr 1948: 144)

For Bohm, by contrast, the mathematical formalism of quantum mechanics describes what *actually* happens in the quantum world, especially when it comes to the interactions between quantum objects and the measuring device. The Bohmian theory of quantum mechanics makes claims about elements of physical reality. However, such metaphysical claims come at the cost of the impossibility of observation of the properties of particles with complete precision due to the limits set by quantum equilibrium (Dürr, Goldstein, Zanghì 1992). Therefore, according to Bohm, one can speak of the truth value of a statement about a paradigmatic quantum experiment at any stage of the experiment: before, during, and after the interactions of the quantum particles with the measuring device, although this truth value is experimentally unverifiable with complete precision.

So far, I have shown that the CI shares more philosophical elements with the DN model than BI. However, from the point of view of the DN model, the appearance of the interference pattern in the double-slit experiment is sufficiently explained by *either formalism*, namely the orthodox formalism corresponding to the CI and the de Broglie–Bohm formalism corresponding to BI.

From the point of view of the DN model, on the orthodox formalism, the initial state of the experiment and the wave function form a sufficient data for explanation. One simply plugs the data into the Schrödinger equation and the experimental results follow. Nothing more needs to be done. No metaphysical account or interpretation is required.

The same goes for the de Broglie–Bohm formalism. The only difference is that, in addition to the wave function, we need to include the initial state of the particles and in addition to the Schrödinger equation, we need to include the "guiding equation". Again, the experimental results follow without any need to include metaphysical relations in the explanation.

Let us now assess the DN model's evaluation of the two formalisms from the perspective of each interpretation. Consider the experimental setup of the double-slit experiment. Taking merely the two formalisms stated above, generally the DN model would explain the appearance of the interference pattern formed by the collision between quantum objects and the photographic screen as follows: (a) In the double-slit experiment's setup, photons were emitted toward the plate with two separated parallel slits, (b) it is a law (of quantum superposition) that, in the double-slit experiment's setup, emission of photons toward the plate with two separated parallel slits (with no which-path device) makes an interference pattern on the photographic screen, and (c) the conditions required by the law held.

The CI totally agrees with the DN model that metaphysical accounts must be excluded from the premises of a scientific explanation. According to the CI, only representations of the interactions between quantum objects and the measuring instruments, as phenomena, are describable and publicly communicable in terms of classical concepts (linguistic terms). The term "explanandum" in the DN model also refers to the description of the phenomenon[15] to be explained: "By the explanandum, we understand the sentence describing the phenomenon to be explained (not that phenomenon itself); by the explanans, the class of those sentences which are adduced to account for the phenomenon" (Hempel 1965: 247). Neither the CI nor the DN model would enter the following metaphysical accounts into its explanation or evaluation: The attribution of any properties to the quantum objects or the explication of the nature of such objects as well as the explication of the underlying processes or the quantum interaction between quantum objects and the measuring instrument before, during, and after the *observation* (the act of measurement) has taken place.

The CI would count the quantum superposition principle as a law of nature[16] under which the DN model subsumes the explanation. From the CI's point of view, the DN model's exclusion of the metaphysical relations would not make the scientific explanation of the interference pattern insufficient. According to the CI, one can reliably *equate a quantum theory with the orthodox quantum formalism*. There is no need for a quantum interpretation to be part of the quantum theory.

However, BI would not agree with the CI that the DN model's evaluation of the explanations provided on the basis of any of the two formalisms (the orthodox or the de Broglie–Bohm formalism) is sufficient. The reason is that, as opposed to the DN model and the CI, BI gives priority to *ontological* explanation. According to BI, measurement and statistics are secondary in significance. BI is primarily concerned with what each individual system *is*, that is, with the ontology of the actual systems. So Bohm, Hiley, and Kaloyerou (1987) develop a formalism and an interpretation "solely in terms of what Bell . . . has called 'beables', without bringing in 'observables' except as a spe-

[15] Generally, a phenomenon is the resultant of the interaction between a physical object and the measuring device under well-defined experimental conditions. The essential difference between classical and quantum physics is that the interaction in the quantum domain must at least comprise one quantum and cannot be made arbitrarily small.

[16] Such a law of nature includes phenomena in question and the statistical nature of the tests.

cial case of what is happening among the beables" (Bohm, Hiley, Kaloyerou 1987: 324).[17] Neither the DN model nor the CI would address Bohm's concerns as to "whether we can have an adequate conception of the reality of a quantum system, be this causal or be it stochastic or be it of any other nature" (Bohm, Hiley 1993: 2). In BI, quantum interpretation forms part of the theory — without it, no sufficient explanation of any quantum phenomena can be provided.

To sum up, the CI would explain the appearance of the interference pattern without addressing metaphysical relations. Similarly, the DN model would evaluate such an explanation under the quantum superposition principle without including descriptions of the relevant metaphysical relations in its explanans, since explanantia must have empirical content. BI would not count such an evaluation as sufficient. A sufficient evaluation for BI would also take into account those (ontological) properties of particles that cannot be observed.[18] For example, according to BI, quantum particles are regarded as an inseparable union of a particle and a field. The latter has some new non-classical properties and contains objective or active information (Bohm, Hiley, Kaloyerou 1987: 327). Such a field plays a crucial role in the (causal) explanation of the appearance of the interference pattern in the double-slit experiment. For a sufficient evaluation of an explanation of the double-slit experiment by a model, BI requires ontological properties and relations to be included in the explanans of the model.

The above requirement is fulfilled by Strevens's kairetic account of scientific explanation, which modifies the DN model by allowing the relevant metaphysical relations to be included in the explanans. In modeling explanations, contrary to the DN model, the kairetic account attempts to determine and include those causal networks that are difference-making and explanatorily relevant to the occurrence of the explanandum.

3. STREVENS'S KAIRETIC ACCOUNT OF EXPLANATION

An appropriate infusion of metaphysical relations into the DN model should modify it in two respects. First, it should make the model sensitive to the asymmetry of some explanations. Second, it should prohibit explanatory irrelevancies. This is what Strevens's kairetic account does to provide an acceptable theory of explanation. However, as I will argue, in the quantum do-

[17] See also (Shafiee, Maleeh, Golshani 2008).

[18] This is why the theory is called "hidden variable" theory.

main, there is still something missing from the account. Namely, it does not *clarify* the role of quantum interpretations as a context or an inseparable part of any quantum theory.

3.1. STREVENS'S MODIFIED CLASSICAL APPROACH TO DIFFERENCE-MAKING

In his kairetic account of explanation, Strevens depicts two major approaches to the solution of the problem of insufficiency of the original DN model: the causal approach and the unification approach. According to the causal approach, the asymmetric feature of the explanation mirrors a causal asymmetry, which motivates the adherents of this approach to think of causation as the fundamental ingredient of explanation. What explains an event in the causal approach is the event's causal history.

On the unification approach, scientific explanation is a matter of providing a theory that unifies a range of different phenomena. According to Kitcher's (1981, 1989) unificationist account of explanation, an event is explained by deriving the occurrence of it using a theory that unifies different phenomena better than other theories.

The kairetic account tries to unify the two approaches. While causal in spirit, when it comes to the notion of *difference-making*, it borrows the technical apparatus of the unification approach. Strevens reaches his kairetic account of difference-making step by step, starting from what he calls the "modified classical account". Then, showing the limitation of the latter account, he develops his kairetic account. In what follows, both accounts are briefly described. Note that, in this paper, I am concerned with Strevens's account of the explanation of events (not laws) as it appears in his 2004 paper.

To resolve the problems associated with the DN model, namely its insensitiveness to the asymmetry of explanation and its inability to prohibit irrelevancies, Strevens proposes his modified classical account of difference-making, according to which for the occurrence of an event *E*, a set of conditions which includes both events and laws is sufficient only if the conditions jointly entail the causal production of *E*. The modified classical account is valid, Strevens holds, if the explanandum is also *deterministically produced*. According to his account, then, the difference-makers for an explanandum *E* are determined by: (1) finding a set of actual initial conditions and laws sufficient to causally produce *E*;[19] (2) removing from the causal model anything that is not

[19] The representation of such laws and conditions is called a veridical deterministic causal model for *E*. By calling the model "veridical", Strevens emphasizes that the conditions are the actual causal influences on the production of *E*.

necessary for the causal production of E, that is, removing everything from the model that does not play a role in the entailment of E (Strevens 2004: 162-163). Strevens calls this the "eliminative procedure", which yields only difference-makers that are explanatorily relevant to the occurrence of E — an *explanatory kernel* for E.

The eliminative procedure treats the elements of a causal model as atomic. This imposes an important limitation on the modified classical account: The eliminative procedure can only remove the unwanted elements of the causal model, but cannot modify them. For example, to explain the breaking of a window, we do not want the *exact* mass of the brick, say 3 kg, to be a difference-maker, but a range within which, say between 1 and 5 kg, the difference is made. Therefore, the modified classical account of difference-making ought to be amended so that, in the case of the mass of the brick, for example, it adopts an approximate amount, not an exact one. Such a modification uses the technical apparatus of the unification approach to transform the modified classical account of difference-making into the kairetic account as the final destination.

3.2. THE KAIRETIC ACCOUNT OF DIFFERENCE MAKING

To achieve the above task, Strevens introduces the notion of "abstraction", itself defined in terms of "generation":

> One model M generates another model M' just in case (a) all causal factors explicitly mentioned by M are also explicitly mentioned by M', and (b) M' says at least as much as M, or a little more formally, every proposition in M is entailed by the propositions in M'. Intuitively, if M generates M', then M' may be obtained by adding some additional causal details to M's description of a causal process. Abstraction I define as the inverse of generation; that is, a model M is an abstraction of another model M' just in case M generates M'. (Strevens 2004: 167)

Construed in this way, step 2 of the eliminative procedure stated above can be amended: (2') making the causal model as abstract as possible without invalidating its entailment of the fact that E is causally produced. According to Strevens (2004: 168, 170), the degree of abstractness of a model is proportional to the number of possible physical systems satisfying the model.

Finally, we should forbid making a model more abstract by putting it in a disjunction with another model that is not a difference-maker. Here, the notion of "cohesion" comes into play. A model is maximally cohesive if, in every system satisfying the model, every causal element in the model plays a role in the production of the explanandum. In other words, the cohesion of a model measures the degree to which the same kinds of difference-makers act in every physical system satisfying the model (Strevens 2004: 171).

Thus, according to the final version of the kairetic account as it appears in (Strevens 2004), *K* is the explanatory kernel corresponding to *M* as a veridical causal model for an event *E* if *K* generates *M* and entails *E*, while best satisfying the conditions of generality and cohesion. In such a case, any causal factor appearing in any kernel for an event *E* counts as a difference-maker (Strevens 2004: 173).

The kairetic account is not confined to the macroscopic domain. Once its conditions are satisfied, the account is also applicable to the quantum world, that is, where the Planck's constant *h* cannot be neglected. More importantly, the account is flexible in providing sufficient explanation of the double-slit experiment, both in the context of the CI and BI, once one adopts one of the interpretations. In such a case, as I will argue, the key elements of the kairetic account are determined by the presupposed interpretation. However, as we will see in the next section, the role of quantum interpretations in quantum theory is either ignored or not sufficiently clarified in the kairetic account.

4. THE KAIRETIC ACCOUNT AND THE EXPLANATION OF THE DOUBLE-SLIT EXPERIMENT

Let us compare two scenarios that cry for an explanation: the famous story of the death of Rasputin and the appearance of the interference pattern in the double-slit experiment.

In the former, Rasputin's assassins poisoned his teacakes, but they failed to kill him. Then they shot him twice; still he did not die. Then they threw him through a hole in the ice into the river Neva with tied hands and feet. He drowned. The explanation of the death of Rasputin suggested by the kairetic account states "(a) that Rasputin was bound and thrown into the river, (b) that it is a law that people bound and thrown into the river in such and such conditions invariably die, and (c) that the conditions required by the law held" (Strevens 2004: 166).

The above model is a causal veridical one that entails Rasputin's death. Removing event (a) will invalidate the entailment, so (a) is a difference-maker. The model also excludes non-difference-making elements as disjuncts and is therefore cohesive. It seems that the kairetic account is successful in explaining Rasputin's death. Note that the DN model would have provided exactly the same explanation as the kairetic account. The difference is that the kairetic account provides a technical apparatus to ensure that the relevant causal relations have been taken into account and the irrelevancies are prohibited.

Now consider the setup defining the double-slit experiment with no which-way devices attached. According to the kairetic account, the appearance of the interference pattern is explained by stating (a) that, in the double-slit experiment's setup, photons were emitted toward the plate with two separated parallel slits, (b) that it is a law (of quantum superposition) that in the double-slit experiment's setup, emission of photons toward the plate with two separated parallel slits (with no which-way device) makes an interference pattern on the photographic screen, and (c) that the conditions required by the law held.

Note that, in the above setup, the width of the slits is smaller than the wavelength of the monochromic light emitted. Also, compared to the separation of the slits, the distance between the plate with the two slits and the photographic screen is large enough. With such antecedent (initial) conditions, the interference pattern will always appear regardless of other parameters, making the model as *abstract* as possible (the cohesion of the model will be discussed shortly).

From the CI's point of view (or in the context of the CI), the above model fulfills all the requirements of the kairetic account, since:

(1) In the context of the CI, the model is a veridical deterministic causal account of the appearance of the interference pattern.

An adherent of the CI may pose the following objection to the above claim: The kairetic account assumes that the explanandum is causally deterministically produced. However, according to the CI, at the time of the measurement, the system behaves in an intrinsically probabilistic manner. The answer to this objection is that, while according to the CI, the particular places where the particles land on the photographic screen are *intrinsically probabilistic*, the appearance of the interference pattern itself is not. That is, if the initial conditions of the setup are satisfied, the interference pattern will deterministically appear. Indeed, both the CI and BI construe the appearance of the interference pattern after the act of measurement as a deterministic event. They differ in that, according to the CI, one has a distribution of positions *after* the measurement, whereas, according to BI, there is a distribution of actual values all the time, regardless of the measurement process (Whitaker 1996: 246).

It should be noted that the conception of "phenomena" in the CI requires the indefinability and inconceivability of quantum objects. The wholeness of Bohr's phenomena refers to the indivisibility of quantum objects. According to the CI, attributing any property to any quantum objects and their *behavior* before, during, or after the act of measurement is impossible. This makes the CI a "non-causal" interpretation in terms of classical physics and the conventional meaning of the term "causal". So, here, the term "causal" must be understood in a Hempelian sense. In this context, neither Strevens's kairetic account nor the CI would have any problem with using the term "causal" in the Hempelian manner.

In his *Studies in the Logic of Explanation*, Hempel gives an account of causal explanation as follows:

> Thus, the event under discussion is explained by subsuming it under general laws, i.e., by showing that it occurred in accordance with those laws, in virtue of the realization of certain specified *antecedent conditions*. (Hempel 1965: 246)

In the next paragraph, he elaborates:

> Thus, here again, the question "*Why* does the phenomenon occur?" is construed as meaning "according to what general laws, and *by virtue of what antecedent conditions* does the phenomenon occur?" (Hempel 1965: 246)

And, more explicitly:

> If *E* describes a particular event, then the antecedent circumstances described [by the singular sentences of the explanans] may be said jointly to "cause" that event. (Hempel 1965: 250)

In this sense, the above model is causal.

(2) Anything not necessary for the causal production of the interference pattern has been removed.

For example, the following proposition has been removed from the causal model as not being a difference-maker and veridical: "Each particle passed through one slit and was causally guided by its associated wave that passes through both slits".

So, proponents of the CI would evaluate the kairetic account as sufficient in modeling the appearance of the interference pattern. From the CI's point of view, the above model allows the formalism of the orthodox quantum mechanics to use the Schrödinger equation, once the initial state of the experiment and the wave function are known.

However, according to BI, the model would not provide a sufficient explanation of *why the interference pattern rather than a particle-like pattern appears*. The same goes for the way the kairetic account would model the explanation of the appearance of the interference pattern merely on the basis of the de Broglie–Bohm formalism.

Here, the kairetic account deviates from the DN model in its ability to include the relevant metaphysical relations in its explanans. Although not experimentally verifiable with complete precision, the kairetic account does allow in its explanans the inclusion of the proposition "Each particle passed through one slit and was causally guided by its associated wave that passes through both slits" as a difference maker and veridical *in the context of BI*. According to BI, the pilot wave *actually* guides the particles so that they pass through one of the slits. Therefore, in the context of BI, the kairetic account would include the latter proposition in its explanatory kernel for the appearance of the interference pattern. In other words, to model the explanation of the appearance of the interference pattern in the double-slit experiment, BI requires the kairetic account to necessarily include the relevant metaphysical relations in its premises before the measurement has taken place. The kairetic account would consider such an inclusion as legitimate.

Once an interpretation is adopted, it is also possible to check the cohesion of a model provided by the kairetic account in the context of an adopted interpretation. According to the CI, before measurement, a model that includes a description of the wave-quantity (the wave-function) and the particle-quantity (the position) of the quantum object in its explanatory kernel is radically disjunctive and so, minimally cohesive. On the other hand, BI holds that the CI overemphasizes the role of measurement. BI stresses that the explanation is incomplete unless it includes a description of how the particle-aspect of the quantum object is guided by the wave-aspect of it. As we can see, the cohesion of a model is determined by the interpretation we presuppose.

Let us summarize this section by saying that by taking into account the relevant metaphysical relations and properties in an appropriate way, contrary to the DN model, the kairetic account succeeds in providing a successful model of explanation in both macroscopic and quantum domain, from the point of view of both the CI and BI. However, a necessary condition for a model of explanation that evaluates the explanations of phenomena in paradigmatic quantum experiments is to adopt an interpretation. This is ignored by the kairetic account (or at least not sufficiently clarified). Once an interpretation is chosen, the key elements of the kairetic account can successfully be determined. The DN model does not have such potential.

The determination of the key elements of the kairetic account by an interpretation also makes it possible for an interpretation to evaluate the way the kairetic account models an explanation in the context of an adopted interpretation. Such a relation between models of explanation and quantum interpretations can be generalized to any model of explanation and any interpretation of quantum mechanics.

CONCLUSION

Sufficient scientific explanation of quantum phenomena in paradigmatic quantum experiments requires presupposing a quantum interpretation either as a context according to which a quantum formalism can sufficiently explain a quantum phenomenon (as in the case of the CI) or as part of a quantum theory (as in the case of BI). A quantum interpretation may (as in the case of CI) or may not (as in the case of BI) require the inclusion of the relevant metaphysical relations in the explanans. This makes a quantum interpretation a necessary element of scientific explanation. The adopted interpretation, then, would determine the relevant explanans. Equivalently, in any model of explanation, it is possible to evaluate the sufficiency of an explanation by a quantum theory only in the context of a quantum interpretation. The above claim can be generalized to any model of scientific explanation.

Finally, one may object that, contrary to the claim of this paper, the necessity of adopting an interpretation of quantum theory in models of scientific explanation becomes almost trivial, once there is a solution to the measurement problem. In response, we need to remember that the measurement problem itself has been the main source of different interpretations of quantum mechanics. In other words, to give a solution to the measurement problem, we need to adopt an interpretation. Therefore, not only does addressing the measurement problem not make it trivial to include a quantum interpretation in our models of scientific explanation, but it also supports the necessity of such an inclusion.

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