Quantum Mechanics and Relational Realism: Logical Causality and Wave Function Collapse

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Abstract: *By the relational realist interpretation of wave function collapse, the quantum mechanical actualization of potentia is defined as a decoherence-driven process by which each actualization (in "orthodox" terms, each measurement outcome) is conditioned both by physical* and *logical relations with the actualities conventionally demarked as "environmental" or external to that particular outcome. But by the relational realist interpretation, the actualization-in-process is understood as* internally related *to these "enironmental" data per the formalism of quantum decoherence. The concept of "actualization via wave function collapse" is accounted for solely by virtue of these presupposed logical relations—the same logical relations otherwise presupposed by the scientific method itself—and thus requires no "external" physical-dynamical trigger: e.g., the Gaussian hits of GRW, acts of conscious observation, etc. By the relational realist interpretation, it is the physical and logical relations among quantum actualities (quantum "final real things") that drives the process of decoherence and, via the latter, the logically conditioned actualization of potentia. In this regard, the relational realist interpretation of quantum mechanics is a praxiological interpretation; that is, these physical and logical relations are ontologically active relations, contributing not just to the epistemic coordination of quantum actualizations, but to the process of actualization itself.*

In the rapidly broadening and often turbulent wake of philosophical assessments and interpretations of the quantum theory, the task of comparison and contrast is greatly eased by considering the following: Any assertion as to the ontological significance of quantum mechanics—especially the relationship between wave function collapse and "reality" (observable or otherwise)—presupposes at least *some* commitment to the general Aristotelian concept of substance. Substance in this regard does not necessarily entail conventional conflation with the concept of physical matter; rather, it is understood to be "the essence of a thing . . . what it is said to be *in respect of itself*" (*Metaphysics* Z.4. 1029b14). Substance is the essence and definition of a thing such that the thing defined is further reducible neither physically or conceptually. The dipolar "actual occasion" of Alfred North Whitehead is perhaps the most revolutionary modern rehabilitation of the classical notion of substance for two reasons: First, the physical and conceptual features of the actual occasion are mutually implicative poles of a single substance rather than mutually exclusive essences of separate substances; and second, an actual occasion "in respect of itself" can never be abstracted from its internal relations with other actual occasions.

As applied to the interpretation of quantum mechanics, many of the more infamous conceptual difficulties—the measurement problem, the problem of state reduction, etc.—can be traced to an uncritical acceptance of the classical conception of substance, further speciated via the dualism of Descartes, into mutually exclusive physical and conceptual realities. Likewise, it can be argued that the Whiteheadian renovation of the classical concept of substance as a repudiation of Cartesian dualism paves a sound pathway around these difficulties—a pathway that is, by Whitehead's own *desiderata* for speculative philosophy, both coherent and empirically adequate.

Despite the displacement of Aristotelian physics with the modern scientific method and ultimately the quantum theory, the concept of irreducible units of "substance"—whether these be understood as units of energy and matter, conception, perception, psychophysical experience, or otherwise—remains the hypothetical object of modern, fundamental physics. Aristotle writes, "Definition and essence are primarily and without qualification of substances" (1030b4-6). And it is here, at the point of physically and mathematically defining the irreducible units of existence that the various ontological interpretations of quantum mechanics find their categories. Indeed, one could argue that the key philosophical implications of any particular interpretation of quantum mechanics ultimately derive from, or at least must be compatible with, the interpretation's particular definition—implicit or explicit—of substance.

It is no overstatement to suggest that every philosophically significant interpretation of quantum mechanics has entailed either a proposed refinement or repudiation of the Cartesian dual-substance metaphysical scheme which today remains tacitly paradigmatic in the popular, scientifically informed Western worldview. By this dualistic paradigm, substance is either a unit of thought or a unit of physical extension. If the latter, it falls completely within the purview of physics; if the former, it is typically understood as transcending a purely physical reductive definition.

Whether or not a particular interpretation of quantum mechanics makes reference to the issue, careful attention to an interpretation's implicit or explicit definition of "substance"—that is, how the interpretation defines the fundamental quantum actuality as "final real thing"—is crucial to any meaningful philosophical exploration of the interpretation. In that regard, one finds four general categories of ontological interpretation of quantum mechanics:

Transcendental realist interpretations

By these interpretations, quantum mechanics is understood to describe not the substance of Nature, but rather how we coordinate our experiences of Nature. By this admonition, the difficulty of mutually exclusive ontological substances—physical and mental, extension and conception—is relieved by the concept of mutually exclusive and complementary epistemic coordinations of experience. Wave function collapse by such interpretations signifies only the epistemic schematization of our physical and conceptual experiences of Nature, rather than revealing anything about the substance of Nature herself. While the reality of Nature is acknowledged in these interpretations, no claim is made that quantum mechanics in any way qualifies the substance of reality in the Aristotelian sense, "in respect of itself"—e.g., as physically or mentally substantial.

Examples of such interpretations include that given by Niels Bohr, who wrote, "In physics, our problem consists in the co-ordination of our experience of the external world" such that "in our description of nature the purpose is not to disclose the *real essence* of phenomena but only to track down as far as possible relations between the multifold aspects of our experience" (Bohr, *Atomic* 18).

The Relative State Interpretation of Hugh Everett (more commonly known as the "Many Worlds Interpretation" or MWI) is another example, in the sense that "reality" is defined as the totality of all co-actual (or "compossible" in the Leibnizian sense) worlds. Physical or conceptual experiences of one particular world—e.g., a particular physical "law"—reveal nothing of the "substance" of reality "in respect of itself" since as a totality, Nature wholly transcends any particular physical and conceptual qualifications relative to some "particular" actual world.

Omniphysical realist interpretations

These interpretations attempt to relieve the mutual exclusivity of thought and extension in Cartesian dualism, in particular, the role of "conscious observation" in wave function collapse, by the assimilation of "mental substance" to sheerly physical quantum substance. These might be considered classically reductionist or physicalist interpretations in the sense that they are reminiscent of the approaches to defining substance seen in many of the abstract materialist pre-Socratic philosophers: By defining the fundamental and presumably physical units of existence it was thought that any complex feature of Nature could then be accounted for as derivative. Common to many of these pre-Socratic physical reductionist interpretations was a fundamental physical force or energy that either acted upon or generated these irreducible units of existence—but (problematically) was itself not reducible to these.

Modern examples of such an interpretation include the "pilot-wave" theories of Louis de Broglie (1927)[1] and David Bohm (1952).[2] In lieu of a collapsing wave function, these theories depict fundamental physical substance (again, in the Aristotelian sense of fundamental things-in-themselves) as point-particles that always occupy precisely defined and determinate regions of space—i.e., no quantum indeterminacy due to the mechanics of wave function collapse. Instead, the wave function is understood to be a mathematical description of a "pilot wave" that accompanies each particle, guiding its motion in a manner similar to that described by classical particle-field dynamics. Bohm called this hidden pilot wave the "quantum potential force."

A similar force is proposed in the Spontaneous Localization Interpretation of GianCarlo Ghirardi, Alberto Rimini, and Tulio Weber (GRW); theirs, however, is a physical, dynamical wave function collapse mechanism which they incorporate into the quantum theory via the addition of a stochastic term to the Schrödinger equation. This term represents a kind of Gaussian flash or pulse which then triggers the actualization of a potential outcome state of the system "hit" by the pulse. While the probability of a subsequent "hit" is conditioned by the shape of the prior wave function, thus allowing for the concept of conditioned physical causality, the fundamental process driving the hits is purely stochastic. By this interpretation, wave function collapse is no longer predicated upon the interaction of the system with some particular "observer." Instead, Nature herself, via the stochastic Gaussian pulses, continuously and spontaneously localizes the wave functions which in turn triggers the actualization of potential outcome states—i.e., the generation of "substance."

The GRW and de Broglie-Bohm interpretations are ultimately omniphysical, classically reductionist substance theories of Nature, driven by physical forces that themselves can be neither described nor accounted for in terms of the definition of "substance" given by the theories. In the pre-Socratic reductionist sense they are, for example, reminiscent of Anaximander's vortex-like eternal motion that brings into being his fundamentally indeterminate physical-elemental substance (his "material cause"); or the principle of *Nous* given by Anaxagoras—a corporeal, physical force that both creates the microscopic atomic actualities (akin to wave function collapse) and generates their formation into complex forms of macroscopic physical reality (akin to the transition from "quantum" to "classical"). And like these analogous forces from ancient philosophy, the GRW pulses and de Broglie-Bohm pilot-waves are incapable of reductive description by their respective theories, and thus incapable of definition in terms of the fundamental concept of substance given by the theories.

This brings to mind Plato's admonition in the *Theaetetus* (201d-210d) that "substance" as the end point of any purely reductive epistemic scheme, when applied to the fundamental description or explanation of Nature, must itself be "unknowable." This is because the end point is, by definition, irreducible; it cannot be known via reduction because there are no "more fundamental" parts. Therefore substance cannot be "known" at all—at least in terms of the same reductive epistemic scheme taken to yield "knowledge" down *to* that deepest level of reduction. And yet the strictures of this purely reductive epistemology prevent not only knowledge of the ultimate "things in themselves"; they prevent knowledge of when that deepest level of reduction has actually been reached—the point where mere description of nature becomes explanation of nature. Thus the foundation of any purely reductive scheme of explicative knowledge is, says Plato, ignorance. In the case of GRW, this is reflected in both the stochastic nature of the Gaussian pulses, and the impossibility of describing either the origin or substance of these pulses in the same terms that physical substance is otherwise defined by the theory. Ghirardi, Rimini, and Weber write, "we do not consider . . . the problem of physical origin of these localizations for microscopic systems. . . . . but we simply postulate that they occur. In this sense we say that they are spontaneous" (471). Ghirardi further writes:

> I would like to stress that [the spontaneous processes of localization] are to be understood as *fundamental natural processes* that owe nothing to interactions with other physical systems or to deliberate actions on the part of conscious observers.

> No observer carries out any measurement: nature itself (Einstein's God?) chooses to induce such a process according to random choices but with precise probabilities. ("Sneaking" 406, 409)

Psychophysical realist interpretations

While the physico-reductive method of modern physics certainly finds its validation in the prediction (and, as often depicted, "control") of nature—namely, that these seem to increase in proportion to the depth of physical reduction—the Platonic chasm separating description of nature and explanation of nature nevertheless remains unbridgeable by a purely reductive epistemology, for the reasons discussed above. GRW and the omniphysical interpretations repudiate the Cartesian appeal to a "second fundamental substance" (thought) as a method of bridging the chasm; the quantum theory, by these interpretations, need not appeal to the idea of "observer-dependent" physical reality. But this is only achieved by proposing a second "fundamental substance" of their own—a purely independent, stochastic process that is indeed "physical," but very different from the interactive, non-stochastic physical reality this process is posited to generate. In that sense, GRW and the omniphysical interpretations are open to the same criticisms that have traditionally undermined the Cartesian dualistic scheme.

By contrast, the transcendental realist interpretations avoid the difficulty by refusing to even attempt such a crossing from description of nature to explanation of nature, from epistemology to ontology. By treating the wave function and its reduction as merely epistemically significant, the transcendental realist interpretations such as that posited by Bohr make no explicit attempt to *ontologically* schematize nature in terms of the interaction of "observing" subject with measured object. Thus Bohr is able to stipulate that the measuring apparatus always be understood "classically" without worrying about how, precisely, a physical substance "defined" classically according to classical rules might interact with a physical substance defined quantum mechanically according to wholly incompatible rules. Since the definition of physical substance by this interpretation is purely pragmatic and epistemic, rather than a metaphysical "definition" in the Aristotelian sense, the fact of mutually incompatible, "complementary" descriptions of Nature's fundamental physical constituents could be characterized as philosophically unproblematic. According to Bohr, any coherent philosophical understanding of quantum mechanics must accept "the impossibility of any sharp separation between the behaviour of atomic objects and the interaction with the measuring instruments which serve to define the conditions under which the phenomena appear" ("Discussion" 210).

Nevertheless, the lure toward assigning at least some type of ontological significance to the wave function and the potentia it represents found its way into the writings of the innovators of the orthodox, "pragmatic" interpretation of quantum theory—the so-called "Copenhagen Interpretation." Indeed, since the theory was intended by its innovators to be a universal physical theory, the lure toward attempting at least some sort of ontological schematization of wave function collapse, despite any disclaimer of pragmatism, is entirely understandable. For example, if, as Bohr asserted, there is no "real" separation between measuring apparatus and measured system, then likewise there is no "real" separation between apparatus, system, and their external environment. Indeed, such connections are a requirement given that quantum mechanics is applicable only to closed systems, and if the concept of "closed system" is given ontological significance, then the only truly closed system is the universe itself.

One implication is that every measurement interaction somehow involves the entire universe of all facts—an idea clearly alluded to by Heisenberg, for example, when he writes: "the transition from the 'possible' to the 'actual' takes place as soon as the interaction of the object with the measuring device, and thereby with the rest of the world, has come into play" (*Physics* 54-55).

In a similarly inspired proposal, John von Neumann held that if quantum theory were indeed a universal—i.e., ontologically significant—theory, then an epistemic characterization of the measuring apparatus (and measuring observer) as "classical" per the suggestion of Bohr is more properly understood as an epistemic *approximation* of an underlying, universal, quantum mechanical definition of the measuring apparatus and measured system. Furthermore, this definition would extend even to the conscious observer of the apparatus—and in that sense, the philosophical conception of "subject perceiving object" falls under the same quantum mechanical definition by which measuring apparatus and measured system are related.

Von Neumann proposed that the conscious subject-observer, measuring apparatus, and observed object-system be envisioned fundamentally as a chain-like ensemble of quantum mechanically interrelated facts.[3] It was, to be sure, less a philosophical position than it was a coherent way of mathematically accounting for the correlations between the facts constituting the measuring apparatus and the facts constituting that which is measured. Nevertheless, his proposal, coupled with Heisenberg's rehabilitation of the Aristotelian conception of ontologically significant potentia, would elevate the possibility of a coherent philosophical understanding of quantum mechanics to new heights, and generate resounding implications.

Of particular import to the psychophysical realist interpretations of quantum mechanics, the crucial feature of von Neumann's proposal is this: If quantum mechanics is to be a truly a coherent, *universal* theory, the correlation of measured system with measuring apparatus should further extend to the facts constituting that which "measures" the measuring apparatus—in other words, the body and mind of the human observer. In this way, the classical conceptions of "subject of measurement" and "object of measurement" become properly understood as arbitrary abstractions from a more fundamental quantum mechanical characterization of measurement as the correlation of a serially ordered "chain" of quantum actualizations. Every particular subject-object correlation, then, becomes a datum for a subsequent subject-object correlation. Von Neumann suggests that it is only by such a scheme of "psycho-physical parallelism" that the innovative and classically problematic "subjective" features of quantum mechanics might be mediated with the necessary "objective" realism in which modern science is grounded. He writes:

> It is a fundamental requirement of the scientific viewpoint—the so-called principle of the psycho-physical parallelism—that it must be possible so to describe the extra-physical process of the subjective perception as if it were in reality in the physical world—i.e., to assign to its parts equivalent physical processes in the objective environment, in ordinary space. (418)

One of the implications of this interpretation of quantum mechanical measurement is that the unique qualities of a particular observer—a particular actual subject—in some way condition and govern the correlations between that subject and its particular object. In this way, the set of probability outcomes yielded by quantum mechanics for any given measurement in a chain of measurements, such as the chain described above, "fits" the particular qualities of *that* subject within the chain. Von Neumann noted that the quantum mechanical mechanism governing these subject-object correlations is very different from the quantum mechanical mechanism by which a *unique*, purely physical measurement outcome is actualized for any given measurement interaction. For one thing, the mechanism governing subject-object correlations is not "purely physical," but rather has to do with human consciousness; secondly, it does not yield a unique measurement outcome, but rather a mixture of probable measurement outcomes.

These and other distinguishing features led von Neumann to further suggest that a coherent, universal interpretation of quantum mechanics requires that the process of subject-object psychophysical correlation in a quantum mechanical measurement interaction must be distinct from the purely physical process descriptive of a unique outcome in such an interaction. He thus proposes a "Process 1" productive of psychophysical subject-object correlation and the influence of this correlation upon the evolution of the *set of probable measurement outcomes*; and "Process 2" describes the physical actualization of a *unique measurement outcome* from among the matrix of probability outcomes yielded by Process 1. Process 1, in other words, is a non-unitary evolution productive of psychophysical subject-object *correlated* menu of probable outcomes; and Process 2 yields a *unique* outcome via unitary evolution.

It must be noted that although the latter always occurs in practice, it is only confirmable by retrodictive observation rather than predictive specification. And conversely, the "menu" of probability-valuated potential outcome states yielded by Process 1 is never observed in practice. It is purely predictive. Process 1 and 2 are connected in that the unique outcome of Process 2, observed retrodictively, always satisfies the matrix of probability valuated potential outcome states predicted via Process 1. Since quantum mechanics cannot account for the outcome of Process 2—i.e., it cannot account for the existence of actualities (though it can describe their evolution)—Process 2 is merely *descriptive* of the unitary evolution from initial factual subject-object system state to final factual subject-object system state. But Process 1 is *explicative*, in that it accounts for the particular probability outcomes yielded; they are functions of the necessary quantum mechanical correlations between a particular subject (i.e., a particular measuring apparatus) and a particular measured system. Von Neumann writes:

> Why then do we need the special Process 1 for the measurement? The reason is this: In the measurement we cannot observe the system S by itself, but must rather investigate the system $S + M$, in order to obtain (numerically) its interaction with the measuring apparatus M. The theory of the measurement is a statement concerning $S + M$, and should describe how the state of S is related to certain properties of the state of M (namely, the positions of a certain pointer, since the observer reads these). Moreover, it is rather arbitrary whether or not one includes the observer in M, and replaces the relation between the S state and the pointer positions in M by the relations of this state and the chemical changes in the observer's eye or even in his brain (i.e., to that which he has "seen" or "Perceived"). (352)

Beyond the concept of psycho-physical parallelism, however, von Neumann proposes no particular schematization of "consciousness"—a "non-physical" force (or at the very least, a meta-physical force) in the sense that consciousness cannot itself be described or accounted for by quantum mechanics—again, *despite* the latter's function as "fundamental" theory. Indeed, since consciousness is presupposed by this interpretation of quantum mechanics, there is no reasonable expectation that quantum mechanics could possibly be employed to account for that which it presupposes. Nevertheless, consciousness by this interpretation produces physical effects—indeed, physical *reality*, much in the same way that the Gaussian pulse of GRW or the pilot wave of de Broglie and Bohm do. In that regard, the physical function of conscious observation is less a physically justifiable presupposition than a matter of philosophical choice.

In many important respects, the notion of psycho-physical parallelism amounts to a quantum mechanical recasting of Cartesian dualism, and with the same difficulties that confronted Descartes. If, for example, consciousness is meta-physical and produces psycho-*physical* effects like Process 1 reductions of potentia to probabilities, and ultimately wave function collapse representative of a unique *physical* actualization, what is the proposed mechanism of interaction between the meta-physical and the physical? Are conscious "mental" reality and quantum mechanically describable "physical" reality two separate substances in the Cartesian sense? Since they are defined so differently—both physically and philosophically—this would seem to be the case. While Descartes did assert the possibility of casual connection between minds and bodies, he never proposed a rigorous explanation of such interaction.

These difficulties understandably inspire many physicists and philosophers to object to the approach of psychophysical realism for its depiction of consciousness as a Cartesian *deus ex machina*—a meta-physical force by which the physical quantum mechanical substance of reality is generated. A common rebuttal is that psychophysical realism does not go beyond characterizing nature pragmatically, precisely as prescribed by "orthodox" quantum theory—that is, beyond the terms of human experience. This philosophical stricture is self-imposed on the grounds that human experience is a definitive feature of the scientific method, and therefore cannot be sensibly divorced from it.

This stricture is, of course, an uneasy fit with the claims of ontological significance that are equally definitive of the "orthodox" quantum theory and modern science in general (various quantum mechanical cosmological models that include within their scope the origin of the universe itself are one example).[4] Indeed, one often finds within psychophysical realist interpretations language that is clearly ontological in the usual (that is, non-pragmatic) sense of the term, such that "consciousness" is characterized as a real feature of nature herself, rather than merely a feature of human beings experiencing nature.

The fundamental principle of psychophysical realist interpretations of quantum mechanics is perhaps best given by Eugene Wigner:

> It was not possible to formulate the laws of quantum mechanics in a fully consistent way without reference to the consciousness . . . It will remain remarkable in whatever way our future concepts may develop, that the very study of the external world led to the conclusion that the content of the consciousness is an ultimate reality. ("Remarks" 284-302)

For Wigner, the continuous evolution of the state of the measured system as described by the Schrödinger equation is inconsistent with the seemingly discontinuous actualization of a unique outcome state. He suggested that this inconsistency could be remedied by a non-linear modification of the Schrödinger equation, which would account for a dynamical mechanism by which the matrix of alternative potential states is discontinuously reduced to a single state. (Compare this to the stochastic linear modification of the Schrödinger equation proposed by GRW to identical purpose.) Wigner further suggested that the mechanism described by this non-linear modification should be attributed to the influence of the mind of the observer upon that which is measured, which would account for why we never observe superpositions or matrices of alternative states in nature; for the act of observation itself *is* the non-linear mechanism causative of state reduction.

Henry Stapp, perhaps today's foremost advocate of the psychophysical realist interpretation of quantum mechanics, has built heavily upon the foundational work of von Neumann and Wigner, drawing upon the philosophy of William James and Alfred North Whitehead to bridge the Cartesian gap discussed above. In his latest volume, entitled *Mindful Universe*, Stapp writes:

> Wigner's suggestion for dealing with this gross mismatch between the Process 2 generated activities of our brains and the contents of our streams of conscious experiences, evidently stems from a desire to have a rationally coherent *ontological* understanding of nature herself; an understanding of the reality that actually exists. Noting that Process 1 is associated with the occurrence of observable events, and hence the need for an observer, Wigner suggests that the breakdown of Process 2 is due to the interaction of the physically described aspects of nature with the consciousness of a conscious being. *This physically efficacious consciousness stands outside the physically described*

> *aspects of nature* controlled by Process 2. Von Neumann calls it the observer's "abstract ego."
>
> Conscious experiences are certainly real, and real things normally have real effects. The most straightforward conclusion would seem to be that Process 1 specifies features of the interaction between (1), the brain activities that are directly associated with conscious experiences, and (2) the conscious experiences with which those activities are associated.
>
> This solution is in line with Descartes' idea of two "substances" that can interact in our brains, provided "substance" means merely a carrier of "essences." The essence of the inhabitants of *res cogitans* is "felt experience." They are thoughts, ideas, and feelings—the realities that hang together to form our streams of conscious experiences. But the essence of the inhabitants of *res extensa* is not at all that of the sort of persisting stuff that classical physicists imagined the physical world to be made of. These properties are indeed represented in terms of mathematically described properties assigned to spacetime points, but their essential nature is that of "potentialities for the psychophysical events to occur." These events occur at the interface between the psychologically and physically described aspects of nature, and the laws governing their interaction are given by von Neumann. The causal connections between "potentialities for psychologically described [psychophysical] events to occur" and the actual occurrence of such events are easier to comprehend and describe than causal connections between the mental and physical features of classical physics. For, both sides of the quantum duality are conceptually more like "ideas" than like "rocks." (167-68)

Two elements from this passage stand out in relation to the preceding discussion: First, the problem of interaction between "mental" and "physical" substance is attenuated by the characterization of physically extensive substance/*res extensa* as "potentialities for *psycho*physical events to occur" and, alternately, "potentialities for psychologically described events to occur." These descriptions, when taken in the context of the statement that "both sides of the quantum duality are conceptually more like 'ideas' than like 'rocks,'" imply at least a *partial* quantum mechanical assimilation of physical substance to mental/psycho-experiential substance—an approach that directly opposes the omniphysical realist interpretations discussed above (GRW, de Broglie, Bohm.)

Second: There is, at the same time, an explicative appeal to the Cartesian scheme of two "substances" in the ontological, Aristotelian sense of the word.

Indeed, Stapp refers to his interpretation as "Quantum Interactive Dualism." Further, these are "substances that can interact in our brains." That, coupled with the characterization of *res extensa* as "potentialities for psycho*physical* events to occur" implies a relief of Cartesian dualism not by reducing the physical to the mental (or, the objective to the subjective), but rather by reducing the dualism itself to a psychophysical monism, where Cartesian "physical" and "mental" substances are recast as physically and psychologically describable aspects of Nature, whose fundamental constituents are quantum psychophysical events.

In an effort to further develop the deeper philosophical implications of the psychophysical realist interpretation, Stapp has suggested a correlation between his interpretation and the metaphysical-cosmological scheme of Alfred North Whitehead. At first glance, an obvious point of connection can be made between Whitehead's dipolar actual occasion, with its physical and mental poles, and Stapp's conception of quantum psychophysical event. The benefit of Whitehead's approach, in terms of providing a universal metaphysical framework that can coherently accommodate quantum mechanics, is that both physical and conceptual features of reality are accounted for via the coherent, ontological, non-anthropocentric concept of the dipolar actual occasion as "final real thing." It would seem that the role of "conscious observer/experiencer" required by von Neumann and Wigner could be accounted for by the actual occasions themselves, thus relieving psychophysical realism of its vulnerability to the *"deus ex machina"* critique.

The difficulty is that in Whiteheadian metaphysics, the "mentality" of the conceptual pole of the "actual occasion" (again, the Whiteheadian "final real thing" in the Aristotelian sense of "substance") is not *conscious* mentality which, by the interpretations of Wigner, von Neumann, and Stapp, is a requirement of their respective interpretations of quantum mechanics. Wigner, for example, explicitly states that his "argument for the difference in the roles of inanimate tools of observation and observers with consciousness—hence for a violation of physical laws where consciousness plays a role—is entirely cogent so long as one accepts the tenets of orthodox quantum theory and all their consequences" (*Symmetries* 178).

Likewise, Stapp writes:

> Reduction events cannot act microscopically on individual particles. That would destroy the oft-observed interference effects. So we do not have end-to-end "panpsychism." Indeed, von Neumann's analysis of the measurement problem shows that it is nearly impossible to establish, below the level of *human* involvement, any failure of the unitary law (Process 2) of purely physically determined evolution . . . At

> present, we lack the empirical evidence needed to specify, on objective scientific grounds, the details of the embedding non-anthropocentric ontology which Whitehead's ideas demand. (106-07)

By contrast, for Whitehead, the "final real things" constituting the substance of Nature come into being without the need of conscious observation or intervention. Thus Stapp proposes several major modifications of Whitehead's metaphysical cosmology to bring it in line with the conscious-observer-dependent reality described by the psychophysical realist interpretations of quantum mechanics in general, and his program of Quantum Interactive Dualism in particular.

In arguing for the need for these modifications, Stapp claims in the above passage that a non-anthropocentric, Whiteheadian-compatible ontological interpretation of quantum mechanics—i.e., one that does not depend upon conscious observation—is incapable of unique specification due to lack of empirical evidence. In fact, there are more than a few such interpretations under active theoretical and experimental development. The previously discussed GRW program is one, as are a number of decoherence-based approaches[5] (environmental decoherence, intrinsic decoherence, the decoherent histories approach, among others), which will be explored further in the next section on the relational realist interpretation of quantum mechanics.

In terms of the current discussion, however, it should be noted that "consciousness," for Whitehead, is an emergent feature of reality produced by highly complex and enduring "social" integrations of dipolar (i.e., physical-conceptual) actual occasions/"final real things." Such integrations are the foundational organized structural constituents of all macroscopic objects, both inorganic and organic, and only a fraction of the latter are sufficiently complex to engage in "conscious observation." Nevertheless, all actual occasions as substantive "things in themselves" comprise both a physical pole and a conceptual pole. It is by this dipolarity that the efficacy of both, a) *physical causal relation*, and b) *conceptual logical implication*, are schematized, each within its respective pole, yet fundamentally unified as mutually implicative features of every actual occasion. In other words, unlike the Cartesian substance-speciation of thought and extension as mutually exclusive, for Whitehead, the "physical" and the "conceptual" are *mutually implicative* aspects of every actual occasion such that neither feature is capable of definition in abstraction from the other. It is in this sense of mutual implication that the actual occasion is understood as "dipolar" (i.e., like a magnet, whose poles are incapable of definition beyond their mutual implication.) The speculative scheme by which this mutual implication is accounted for is given in careful systematic form in Whitehead's magnum opus, *Process and Reality*. While a detailed discussion of this scheme lies beyond the scope of this essay, certain general features are introduced for the present discussion.

Though actual occasions do not by definition consciously "observe," they do "prehend" both physically and conceptually, which in shorthand simply means they are causally conditioned by both a) the physical aspects of temporally antecedent occasions, and b) the conceptual aspects of logically antecedent occasions. Thus the order of causal relation and the order of logical implication are always correlated in Whiteheadian metaphysics. The conceptual/mental pole entails the logical conditioning (but not determination) of various potential integrations of prehended facts into valuated, alternative forms of definiteness, one of which will be actualized.

As a dipolar monistic-realistic scheme, it is the very essence of Whiteheadian metaphysics that one can neither reduce nor assimilate one pole to the other, nor even coherently conceive of one pole in abstraction from the other given that each requires the other for both its definition, as well as the definition of the actual occasion as "final real thing." As a philosophical framework for Quantum Interactive Dualism, then, Whitehead's dipolar monistic metaphysics would seem to be a difficult fit for the neo-Cartesian dualism which Stapp commends.

The dipolar relational realist interpretation [6]

This interpretation begins with Heisenberg's suggestion that apart from its epistemic significance, there is a sense in which the wave function must be understood to entail at least *some* ontological significance; for the potentia it describes, while not physically *actual*, are nevertheless "real" to some extent given that their probability valuations yield "real" physical outcomes. And indeed, Heisenberg would later insist upon the fundamental reality and function of potentia in this regard. For him, potentia are not merely epistemic, statistical approximations of an underlying veiled reality of predetermined facts; potentia are, rather, ontologically fundamental constituents of nature. They are *things* "standing in the middle between the idea of an event and the actual event, *a strange kind of physical reality* just in the middle between possibility and reality." (*Physics* 41) Elsewhere, Heisenberg writes that the correct interpretation of quantum mechanics requires that one consider the concept of "probability as a new kind of *"objective" physical reality*. This probability concept is closely related to the concept of natural philosophy of the ancients such as Aristotle; it is, to a certain extent, a transformation of the old "potentia" concept from a qualitative to a quantitative idea" ("Development" 12).

The relational realist interpretation of quantum mechanics begins with this conception of ontologically significant potentia—"real" apart from their actualizations, but "non-actual" until actualized quantum mechanically. Within that context, this interpretation incorporates foundational features of various theoretical programs that explicitly explore the phenomenon of quantum decoherence as a process integral to quantum mechanical actualization of potentia (i.e., "wave function collapse"): In particular, the work of Wojciech Zurek,[7] Roland Omnès,[8] Robert Griffiths,[9] and Murray Gell-Mann & James Hartle.[10] A great deal of experimental work has been committed to the study of quantum decoherence in recent years, and it has become a robust topic of inquiry in physics. While there is as yet no empirically validated "generic" model for decoherence, the basic features of the theory have been sufficiently established to warrant careful philosophical exploration. The dipolar relational realist interpretation is one such exploration.

By this interpretation, the quantum mechanical actualization of potentia is defined as a decoherence-driven process by which each actualization (in "orthodox" terms, each measurement outcome) is conditioned both by physical *and* logical relations with the actualities conventionally demarked as "environmental" or external to that particular outcome. But by the relational realist interpretation, the actualization-in-process is understood as *internally related* to these "environmental" data per the formalism of quantum decoherence. The concept of "actualization via wave function collapse" is accounted for solely by virtue of these relations, and thus requires no "external" physical-dynamical trigger—the Gaussian hits of GRW, acts of conscious observation, etc. By the relational realist interpretation, it is the physical and logical relations among quantum actualities (quantum "final real things") that drives the process of decoherence and, via the latter, the actualization of potentia. In this regard, the relational realist interpretation of quantum mechanics is a *praxiological* interpretation; that is, these physical and logical relations are *ontologically active relations*, contributing not just to the epistemic coordination of quantum actualizations, but to the process of actualization itself.

The wave function/density matrix represents the totality of potential relations for that actualization-in-process—a coherent superposition of both logical and illogical potential relations, represented by the diagonal and off-diagonal terms of the density matrix, respectively. The latter, for example, would represent relations violating the Principle of Non-Contradiction (PNC), the theoretical actualization of which has been famously represented by the concept of an "actual" Schrödinger Cat, both alive and dead at the same time.

As described via von Neumann's "Process 1" the process of quantum mechanical actualization/state evolution entails a "reduction" of this density matrix whereby the "illogical," off-diagonal terms are eliminated from the coherent superposition, rendering it "decoherent." The diagonal terms which survive this logical conditioning each represent a potential outcome actualization as before, but with an important new qualification: They are now valuated as *probabilities* and as such satisfy a second presupposed logical *desideratum*—the Principle of the Excluded Middle (PEM). Thus, the probable outcome states of the reduced density matrix are both mutually exclusive in satisfaction of PNC (i.e., at *most*, one will be actualized), and exhaustive in satisfaction of PEM (i.e., at *least* one will be actualized), since the probabilities for each possible outcome state must sum to unity.

Perhaps most important, this explicit acknowledgement of PEM as a logical desideratum of quantum mechanics, presupposed by the very concept of probability as absolutely fundamental to the mechanics, obviates the need for some physical dynamical "mechanism" that actualizes the final, unique outcome state from among the reduced matrix of probable states. The actualization of *one* probable state is presupposed by the logical, probabilistic nature of the mechanics and the mathematics by which the mechanics are described; the fact of a unique outcome need not (and indeed, logically cannot) be accounted for *by* the mechanics which necessarily presuppose it. Likewise, quantum mechanics cannot account for the existence of unique, actual, system-detector-environment states *prior* to measurement, similarly presupposed by the theory. In the same way that we easily stipulate the actual existence of the system-detector-environment as a presupposition for the very possibility of measurement, a unique actual outcome subsequent to measurement is similarly presupposed by quantum mechanical measurement. The fact that such measurement yields a set of *probability-valuated* outcome states alone guarantees the actualization of one of those states.

Put another way, quantum mechanics can no more account for the existence of unique actuality via some purely efficient "cause of wave function collapse" than classical mechanics can account for the existence of matter via descriptions of motion and inertia. Unique actual existence characterized by logically conditioned causality—explicitly acknowledged in the relational realist interpretation—is a presupposition of both quantum and classical mechanics. The difference is that classical mechanics provided philosophers of the early modern period no readily discernable indication of *how* the order of physical causal relation correlated with the order of logical implication. The resulting philosophical proposals either attempted to reduce the logical order to the physical causal order (e.g., the philosophy of Locke), to reduce the causal order to the logical order (e.g., Spinoza), to depict the correlation of the logical and causal orders as a schematization by which we experience the otherwise transcendent "things in themselves" (e.g., Kant), or to deny the necessary presupposition of either order (e.g., Hume).

Like classical mechanics, quantum mechanics raises the same issue and has generated analogous philosophical approaches: The GRW approach generally comports with the philosophy of Locke, the transcendent realist approaches of Bohr and Everett generally comport with the philosophy of Kant. The advantage of the relational realist interpretation and its reliance upon the concept of logically conditioned decoherence is that it offers a more detailed proposal for how, precisely, the logical order correlates with the physical-causal order as exemplified by modern quantum mechanics. It does so by way of describing quantum actualities, quantum "things in themselves," as fundamental *becomings* rather than fundamental *beings*. Quantum mechanics, when interpreted via those approaches that explicitly acknowledge the process of decoherence, exemplifies three primary features of these becomings:

1) They are fundamentally relational, not just in *ad hoc* epistemic terms of "measuring apparatus" and "measured system" but also at the ontological/substance level of quantum actualities, such that quantum mechanical actualities both internally and externally "environmental" to "system" and "detector" are involved. In this way, all actualities within the closed system of the universe are considered in logical relation quantum mechanically, thus allowing for a coherent ontological (universal) interpretation.

2) These quantum mechanical relations are logically governed potential integrations. It is the explicit incorporation of these relations into logical equivalence classes, *relative to a particular actualization, with its particular preferred basis,* that provides sufficient degrees of freedom for a logical negative selection process. This process is represented mathematically by the trace over, elimination of off-diagonal terms, and by reduction to the reduced density matrix with its mutually exclusive and exhaustive probability-valuated potential outcome states.

3) The logical integrations of coherent, superposed potentia into the decoherent, mutually exclusive and exhaustive probable outcome states represented by the reduced matrix can be correlated with von Neumann's

Process 1; and likewise, the physical fact of unitary evolution to a unique outcome state can be correlated with his Process 2. Thus the logical features of Process 1 and the physical features of Process 2 are *mutually implicative in every quantum mechanical actualization*, and it is in this sense that every such actualization is a dipolar (logical and physical) relational "becoming."

There have been two major criticisms of interpretations of quantum mechanics grounded in the concept of decoherence. The first is that they do not "physically account for" wave function collapse—that is, the actualization of a unique outcome state from among the menu of probable outcome states represented by the reduced density matrix. One answer to this criticism was given above: namely that such actualization is a logical presupposition inherent in the fact that the potential outcome states represented by the reduced density matrix are *probability*-valuated outcomes, mutually exclusive (in satisfaction of PNC) and exhaustive (in satisfaction of PEM). It is because of these two logical desiderata that *some* actual outcome is guaranteed (by PEM) and that it will not be some actualized superposition (by PNC)—i.e., an actualized Schrödinger Cat. Thus the fact that quantum mechanics terminates in probabilities rather than unique actualities is no theoretical deficiency or evidence of "incompleteness." Nevertheless, the inability of decoherence-based interpretations to "account for actuality" remains a source of criticism. This is likely driven in large measure by the fact that the "problem" of wave packet collapse is an infamous one, and its solution by simple denial on logical grounds rings of sophistry for many physicists.

Regardless, the argument remains: First, it is ultimately unreasonable to suppose that quantum mechanics could ever "account" for either 1) the fact of "actuality" which it necessarily presupposes; or 2) the fact that this actuality is logically conditioned, which the theory also necessarily presupposes. Physicist Roland Omnès, whose approach to quantum mechanics can be said to fall within the dipolar relational realist category, puts it thus: "One may consider that the inability of the quantum theory to offer an explanation, a mechanism, or a cause for actualization is in some sense a mark of its *achievement*. This is because it would otherwise reduce reality to bare mathematics (494). Indeed, one could argue that it is typically when fundamental physics reaches beyond its proper task of *describing* nature and presumes to *explain* nature—i.e., account for its existence—that it encounters problems of philosophical incoherence.

Second, capitalizing on the logical features of quantum mechanics in the manner proposed by the various decoherence-based interpretations is in no way a sophistic maneuver given that these same logical features are unavoidably implicit in every aspect of the quantum theory—both the mathematics by which the theory is described, but also, equally important, in the logical nature of physical causality. Advocates of decoherence-based interpretations of quantum mechanics simply make use of logical principles that are already presupposed by the quantum theory and universally evinced in every scientific theory of physical causality. The only difference is that rather than merely stipulating the logical nature of physical causality (or worse, pretending that the scientific enterprise is not founded upon this stipulation as an article of faith), the decoherence-based interpretations explicitly acknowledge and capitalize upon the presupposition of logical causality, applying it mathematically to the "problem" of wave function collapse.[11]

Wojciech Zurek, for example, referring to a paper by Richard Cox,[12] emphasizes that the theory of probability as it is employed in quantum mechanics presupposes the laws of Boolean logic. Zurek writes:

> Intuitively, this is a very appealing demand. Probability emerges as an extension of the two-valued logic into a continuum of the "degrees of certainty." The assumption that one should be able to carry classical reasoning concerning "events" and get consistent estimates of the conditional degree of certainty leads to algebraic rules which must be followed by the measure of the degree of certainty.
>
> This implies that an information processing observer who employs classical logic states and classical memory states which do not interfere will be forced to adopt calculus of probabilities essentially identical to what we have grown accustomed to. In particular, likelihood of c and b (i.e., "proposition c · b") will obey a multiplication theorem:
>
> $\mu\ (c \cdot b|a) = \mu\ (c|b \cdot a)\ \mu\ (b|a)$.
>
> Above $\mu(b|a)$ designates a conditional likelihood of b given that a is
>
> certain. Moreover, μ should be normalized:
>
> $\mu\ (a|b) + \mu\ (\sim a|b) = 1$,
>
> where ~ a is the negation of the proposition a. Finally, likelihood
>
> of c or b
>
> $(c \cup b)$ is:
>
> $\mu\ (c \cup b|a) = \mu(c|a) + \mu(b|a) - \mu(c \cdot b|a)$,

> which is the ordinary rule for the probability that at least one of two events will occur.
>
> In short, if classical Boolean logic is valid, then the ordinary probability theory follows. We are halfway through our argument, as we have not yet established the connection between the μ's and the state vectors. But it is important to point out that the assumption of the validity of Boolean logic in the derivation involving quantum theory is nontrivial. As was recognized by Birkhoff and von Neumann, (Birkhoff, G., and von Neumann, J., 1936, Ann. Math. 37, 823-43) the distributive law $a \cdot (b \cup c) = (a \cdot b) \cup (a \cdot c)$ is *not* valid for quantum systems. Without this law, the rule for the likelihood of the logical sum of alternatives, Eqs. (26), (27) would not have held. The physical culprit is quantum interference, which, indeed, invalidates probability sum rules (as is well appreciated in the examples such as the double slit experiment). Decoherence destroys interference between the einselected states [states "superselected" via their environmental relations]. Thus, with decoherence, Boolean logic, and, consequently, classical probability calculus with its sum rules are recovered . . . Thus, starting from an assumption about the validity of classical logic (i.e., absence of interference) we have arrived, first, at the sum rule for probabilities and, subsequently, at the Born's formula. ("Decoherence" 12-13)

The second major criticism of the decoherence-based approaches is that although the phenomenon of quantum decoherence can be and has been rigorously studied in the laboratory setting, it remains unclear what, precisely, generates decoherence—that is, what are the *physical relata* that generate the required degrees of freedom necessary for logical integration and negative selection of the off-diagonal terms? Typically, decoherence is understood to be "induced" by phase correlations between system and "environment." Spin baths and oscillator baths are two types of experimental arrangements that have been employed to test environmental decoherence. The difficulty is that a number of experiments have yielded decoherence rates that far exceed those predicted by the usual environmental decoherence models—i.e., those restricted to "external" physical interactions.

This has lead some theorists to explore the notion of intrinsic or "internally environmental" relata that, when added to externally environmental relations, might account for the observed decoherence rates. Philosophically, this idea of "intrinsic" sources of decoherence implies the possibility of a substance-definitive conception of decoherence such as that proposed by the relational realist interpretation of quantum mechanics—sources that can be described ontologically as Nature's ultimate constituent "final real things." The relational realist depiction of the latter as quantum mechanical "becomings," discussed above, is certainly compatible with the physical theory of "intrinsic decoherence."

P.C.E. Stamp writes:

> By "intrinsic" sources [of decoherence in Nature], is meant sources which are inevitable in the world as it is, not arising from dissipative processes and perhaps even arising as part of the basic structure of the universe.
>
> Such intrinsic sources of decoherence in Nature, operating even at $T=0$, would not only provide a way of explaining the "emergence of classical physics" in fields ranging from quantum cosmology to condensed matter physics; they would also place a fundamental limit on the observability of quantum phenomena. This would limit the possibility of seeing macroscopic quantum phenomena, and also place fundamental limits on the superpositions required for quantum computing.
>
> Possibilities for intrinsic decoherence mechanisms have already emerged from both low- and high-energy physics. From low-energy physics there has been a suggestion that zero point modes of continuous quantum fields (in particular, the photon field) could cause T=0 decoherence. This has, for example, been suggested as an explanation of the decoherence saturation at low T in mesoscopic conductors. (Mohanty et al., 490)

To the extent that the decoherence-based interpretations of quantum mechanics are at least sufficiently developed to have generated rigorous experimental testing, likewise the philosophical implications of the general principles of these interpretations are equally worthy of careful exploration. In my *Quantum Mechanics and the Philosophy of Alfred North Whitehead*, I proposed that the philosophical innovations inherent in the decoherence-based interpretations correlate closely with those proposed by Alfred North Whitehead in *Process and Reality.* It must be emphasized, however, that my exploration of these correlations was and is not intended as an "explanatory" scheme by which either Whitehead's metaphysics or the quantum theory can be "properly" understood, each in terms of the other. What I explore, rather, is simply the proposition that the fundamental features of Whitehead's speculative metaphysical scheme and his conception of dipolar actuality can be seen as exemplified in those interpretations of quantum mechanics that make use of the decoherence effect. Circularity of validation—whether the physics is to be understood as validating the metaphysics or vice versa—is avoided by acknowledging, in a speculative philosophical context, that the first principles common to both are necessarily presupposed within the proposition and thus incapable of simple proof by deduction or demonstration. These first principles, both logical and ontological, constitute the starting point for exploration, not the end point of explanation.

But beyond merely exploring this proposition, I do attempt to argue for its fitness to the task of interpreting quantum mechanics. I offer this argument in the same speculative philosophical spirit in which Whitehead argued for the fitness of his metaphysical scheme to the task of understanding (though not "explaining") nature—not by the "provability" of his first principles via deduction or demonstration, but by their evaluation against the metrics of coherence and empirical adequacy.

In the most general terms, both decoherence-based interpretations and Whiteheadian metaphysics depict the following:

> 1. Fundamental substance defined as quantum "becomings" ("actual occasions") whose actualization ("concrescence") is predicated upon internal relations with ("prehensions" of) an environment of antecedently settled becomings—i.e., "facts"—the data of the settled world. These relations are both causal-physical, and logical-conceptual in that the physical relations are logically integrated or "objectified"; thus each quantum becoming, when considered as a substantial "thing-in-itself" evinces both a physical pole and a conceptual pole. The term "dipolar" signifies the fact that the physical and logical features of a quantum mechanical becoming are mutually implicative in quantum mechanical actualizations.
>
> 2. The internal relations with the dative environment are logically integrated, first into a "pure state" comprising superdenumerable potential outcome states. These integrations are then further integrated into coarse-grained ("transmuted") equivalence classes, ("subjective forms"). A negative selection process ("negative prehension"), conditioned by the logical principle of Non-Contradiction and fuelled by the massive degrees of freedom yielded by environmental relations, eliminates potentia logically incapable of integration. This is represented by the cancellation of off-diagonal terms and the evolution of the density matrix to the reduced state.
>
> 3. This integration, described by von Neumann's Process 1, results in a probability "valuation" of the remaining potential outcome states. By the Principle of the Excluded Middle, one of these probability-valuated potential outcome states/subjective forms will be actualized, in accord with its valuation—i.e., its probability amplitude.

For Whitehead, the fundamental unit of "substance"—the essence of actual existence—is the actual occasion. By this model, the essence of "being" is "becoming," and the actual occasion is the fundamental, "substantial" unit of becoming. Unlike other substance metaphysical accommodations of quantum mechanics briefly explored earlier in this essay, Whiteheadian "substance" is a dipolar unit of process, or actualization, that entails both a causal-physical pole and a logical-conceptual pole. Unlike the dualistic Cartesian metaphysical scheme, where substance is either a unit of thought or physical extension, in Whitehead's dipolar monistic scheme, each pole is mutually implied within the contextual unity of the actual occasion as a whole.

When actualized, the occasion has its causal efficacy upon subsequent actualizations; and likewise, its process of actualization is affected by both 1) its causal physical relations with the actualities "physically" prior to it in terms of spatiotemporal extensiveness—i.e., within its backward lightcone, per the restrictions of relativity theory. Physical antecedence is reflected, for example, in the statement "*p* causes *q*"; and 2) its logical relations with those actualities "logically" prior to it, per the restrictions of the Principle of Non-Contradiction, among other logical restrictions. Logical implication is reflected in the statement "*p* only if *q*."

Each actual occasion is thus fundamentally a *unit of relation*. In the process of actualization, the becoming occasion is internally related to its dative world of antecedently actualized occasions, and these relations are both causally and logically integrated; and since the actualization is *internally* related to its dative world, the relations form potential histories subsuming *both* the becoming occasion *and* its dative world. Thus, another philosophically problematic conceptual pair, "unity" and "diversity" are also brought into coherence via mutual implication. "The many," writes Whitehead, "become one, and are increased by one. In their natures, entities are disjunctively "many" in process of passage into conjunctive unity" (21). These integrations are always logically governed, such that upon actualization, the occasion is related to the world in a manner free of violations of the Principle of Non-Contradiction, or any other such violation of the logical order. Writ large, the universe is thus described as a networked system of serial routes or "histories"[13] of quantum actual occasions; the integrative internal relations of every actualization constitutive of each route are logically governed such that the orders of causal relation and logical implication are correlated (again, this is a speculative presupposition grounded in the concept of the dipolar actual occasion).

Those interpretations of quantum mechanics that make use of the decoherence effect are unique in their reliance upon the explicit operation of two categories of first principles, ontological and logical. The ontological first principle is that which categorizes actuality and potentiality as two species of reality—a long overdue rehabilitation of Aristotle's signature improvement of the Parmenidean worldview, which depicted "becoming" as pure illusion. The logical first principles are PNC and PEM, without whose presupposition the correlation of causal relation and logical implication would remain wholly unfounded. Science requires that conclusions follow both causally *and* logically from premises and not merely by conjunction, either random or constant; quantum mechanics, by the Heisenberg uncertainty principle, requires that the final outcome state be not only subsequent to the evolution but causally and logically consequent of it.

These two categories of first principles, ontological and logical, are infused throughout Whitehead's Categoreal Obligations. Their governance of the mechanics of Whiteheadian concrescence / quantum mechanical actualization of potentia, in the Platonic sense of μεθεξισ (participation) of "physical fact" in form, and μιμησισ (duplication) of form in physical fact, can be closely correlated with their governance of quantum mechanics, both logically and ontologically. The conceptual scientific difficulties they relieve with respect to the problem of wave function collapse are, as has been discussed, similarly relieved metaphysically. Though the Platonic chasm separating physical fact (e.g. "measurement outcome") from reasoned form (e.g., the wave function/ density matrix and its logically governed reduction) is not bridged certainly, it is bridged speculatively: quantum mechanics and Whitehead's metaphysical scheme are both essays—attempts at crossing, built upon reasonable yet necessarily presupposed first principles. Contingent, mutable physical phenomena are thus correlated with necessary, immutable logical principles. What *appears to be* is thus correlated with what is *reasoned to be*. Physical description and speculative metaphysical explanation find their intersection. That the first principles cannot be accounted for by the mathematical, physical, and metaphysical schemes that presuppose them should not be considered a liability for scientific description or metaphysical explanation, for logically it could not be otherwise. Indeed, it is only by way of first principles that incomplete and often incompatible scientific descriptions of reality, such as those given by classical and quantum mechanics, rise to the level of coherent, albeit ineluctably speculative, philosophical explanation.

Conclusion

Any ontological interpretation of quantum mechanics wherein potentia are characterized as a fundamental feature of reality—whether the interpretation be transcendental realist, omniphysical realist, psychophysical realist, or relational realist—must at some point, address not only the physical relationship between these potentia and the actualities from which they evolve, but also the logical relationship between these potentia and the actualities they evolve to become. For an ontological interpretation to be taken seriously as a philosophical enterprise—i.e., as a genuine speculative attempt and not merely one that retreats to either transcendent reality or to claims of pragmatism when the scheme in fact makes fundamental ontological claims about the universe itself—the interpretation must put forth a coherent and empirically adequate conception of "substance." Without this basic desideratum, it is difficult to see how the interpretation can claim to be an ontologically significant framework by which the philosophical innovations of the quantum theory can be explored as "real" features of nature itself, rather than merely human experiences of nature. For even when an interpretation is characterized as going no further than the latter, it nevertheless makes veiled ontological claims and presuppositions when it specifies, for example, the limitations of these experiences (e.g., qualifying unknowable, transcendent reality as unknowable.) This is because human experience is defined in these theories as being an aspect of nature; therefore any epistemic quantum mechanical schematization of how human beings "experience nature" brings with it a host of ontological implications concerning nature "*in respect of itself*"—that is, in the Aristotelian sense of "substance."

In terms of a rigorous philosophical exploration of the ontological significance of quantum mechanics, in other words, one must be concerned not only with the task of coherent description of potential and probable outcome states and their actualization; one must also endeavor to construct a coherent speculative scheme that attends to the question of why, in terms of the substance of nature, these potential and probable outcome states evolve as they do—from potentiality to probability to actuality—a physical evolution demonstrative of logical causality.

Notes

1. De Broglie, 1315-20.

2. Bohm, *Physics Review,* 180.

3. Von Neumann, 418-20.

4. See, for example, Hartle and Hawking, 2960-75.

5. See, for example: Zurek 2003, 715-75; Myatt, King, Turchette, Sackett, Kielpinski, Itano, et al, 269-73; Mohanty, Jariwala and Webb, 3366–69; Epperson, 2004

6. Epperson, 2009, 19-41

7. Zurek, 2003, 715–85

8. Omnès 1994

9. Griffiths 1984, 219–72

10. Gell-Mann and Hartle, 1994

11. See, for example, Omnès 1994 and Griffiths 2002

12. See R.T. Cox.

13. See Griffiths, 1984 and 2002

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