

Unpacking Quantum Wave Function Collapse: Introduction to the 3-in-1 Ontological Model of Nature

Robert W. Boyer

ABSTRACT

This paper examines major interpretations of quantum wave function collapse, including the orthodox, many-worlds, decoherence, and neorealist interpretations. The interpretations increasingly support quantum reality, and are progressing toward a three-level model of the 'explicate' local, 'implicate' nonlocal, and 'super-implicate' unified field levels consistent with the ancient 3-in-1 Vedic model. This completely holistic model is ontologically rich enough for a logically consistent account of the causal influence of mind over matter, as well as the change from mathematical possibilities to physical actualities without positing quantum wave function collapse.

Key Words: quantum wave collapse, quantum reality, causal wave, conscious intention, Veda

NeuroQuantology 2012; 2:230-251

Introduction

Interpretations of quantum wave function collapse relate to the long-standing philosophical debate between *realism* and *idealism*. Fortunately now the debate involves evidence-based models. The realist assumption of independent real objects existing whether observed or not is fundamental to classical science. It also assumes that for the most part the objective world can be measured without the observer influencing it. As Einstein (In Dickson, 1998; p.154) asserted:

“An essential aspect... of things in physics is that they lay claim, at a certain time, to an existence independent of one another, provided these “objects” are situated in different parts of space... Unless one makes this kind of assumption about the independence of the existence (the “being-thus”) of objects which are far apart from one another in space—which stems in the first place from everyday thinking—physical thinking in the familiar sense would not be possible. It is also hard to see any way of formulating and testing the laws of physics

unless one makes a clear distinction of this kind.”

A major concern of this view is that the observer is independent of the objects observed, but at the same time the observed physical system is said to be *observer-independent* in the sense that the observer is assumed to be inside it and thus the system is not dependent on it. This can be associated with an ‘endophysics’ perspective (Tarlaci, 2012) in which the observer is inside the observed system. But the observer’s conscious mind is not accounted for in the observed physical system, and ends up in an inconsistent way outside it (subject/object independence; mind/matter duality).

In contrast to this physicalist realism view is idealism, an *exophysics* (Tarlaci, 2012) or outside perspective in which the observer is external, and thus the physical system is *observer-dependent*. The idealist view is succinctly summarized in a quote by cognitive neuroscientist Francisco Varela, neurophilosopher Evan Thompson, and cognitive psychologist Eleanor Rosch:

“The idealist...quickly points out that we have no access to such an independent world except through our representations.... In fact, we simply have no idea of what the outside world is except that it is the presumed object of our representations.

Corresponding author: Robert Boyer

Address: Institute for Advanced Research Malibu, CA, United States.

✉ rw.boyer@yahoo.com

Received Jan 16, 2012. Revised April 1, 2012. Accepted April 21, 2012.

eISSN 1303-5150



Taking this point to the extreme, the idealist argues that the very idea of a world independent of representations is itself only another of our representations.... (1993; p.161)”

Interpretations of quantum wave function collapse concern inconsistencies in both physical and quantum theories about the place and role of the observer. This paper shows that a logically consistent resolution requires an ontologically real quantum level beyond the physical.

Taking the physical realist perspective, modern science has progressed with great success applying the objective experimental method at *macroscopic* time and distance scales. But as *microscopic* scales are investigated, the viability of the realist assumption of the independence of observer and observed while also placing the observer in the physical has been severely challenged, a consequence of quantum theory and the model of wave function collapse.

According to the initial orthodox (Copenhagen) interpretation, an elementary matter particle is no particular *thing* prior to being observed or measured. It is characterized mathematically as a *probability wave function*. Only when an observer makes a measurement or observation does the quantum wave function reduce into a concrete classical physical object with definite measurable dynamic attributes in space and time. This gives the observer a crucial role.

Though particles are represented mathematically in classical physics as points in space with *no extension*, in quantum field theory quantum wave potentials are envisioned as having *infinite extension*. Superposed imaginary unbounded quantum waves collapse into discrete particles upon observation. But this glosses over the distinction between the quantum wave function in imaginary mathematical space and classical objects in *real* physical space.

In the orthodox interpretation the quantum wave function was not thought of as physical in the sense of having *real* energy or mass. It was characterized as abstract possibilities or *tendencies to exist*. To make it seem a bit more tangible, it sometimes was imagined as an amorphous wave or cloud of probabilities associated with the concept of *quantum potentia*. This view impelled the question of how to get from the abstract

mathematical quantum wave function to a concrete *real* physical object. This is the *measurement problem*.

To get from the probabilistic quantum wave function to a classical determinate physical object in ordinary time and space, it was argued that there must be a *collapse of the quantum wave function*, theorized to occur *instantaneously* upon observation. The mathematical probabilistic wave function and its theorized collapse were described as unbounded quantum wave potentials that instantaneously transition into a discrete *real* object when observed.

It is curious how an imaginary mathematical quantum wave function could extend throughout the real universe. Equally curious is that the notion of *instantaneous* wave function collapse with no other information in nature precludes any causal explanation about how the collapse occurs, quite odd for scientific theories which usually address cause and effect. The initial orthodox interpretation built a conceptual ‘inviolable wall’ beyond which it was argued that no further answers about the quantum wave function and its collapse are needed or even possible, because there is no additional information in nature.

Although his theory of ‘complementarity’ emphasized both particle and wave properties of objects, the founder of quantum theory physicist Neils Bohr did not explicitly take the step beyond the physical. Rather, he asserted that: “[T]here is no quantum world...only an abstract quantum description (Herbert, 1985, p. 22).” At the quantum level, apparently fundamental randomness and indeterminism take over. Physicist Brian Greene (2004; p.19) expresses concern about this view:

“According to standard quantum mechanics, when we perform a measurement and find a particle to be here, we cause its probability wave to change: the previous range of potential outcomes is reduced to the one actual result our measurement finds.... In the standard approach, the collapse happens instantaneously across the whole universe.... Nevertheless, there is a hitch. *After more than seven decades, no one understands how or even whether the collapse of a probability wave really happens.*”

If there is more to the story, which Einstein and others believed must be the case for an objective world with determinate



natural laws, then the model of instantaneous quantum wave function collapse needs considerable unpacking. That is the objective of this paper.

Schrödinger's Cat Paradox

A well-known thought experiment called *Schrödinger's cat paradox* has been used to illustrate paradoxes of quantum wave function collapse, and again here will be used to set the stage for this overview. A way to describe the paradox is that a cat is inside a steel box and there is no way to look into the box when closed. Inside the box is a Geiger counter with radioactive material that has a 50% chance of one of its atoms decaying within an hour. If the particle decay happens, the Geiger counter will record it and trigger the release of a lethal gas. If no particle decay occurs in the hour, the gas would not be triggered and the cat would remain alive.

Given the interpretation that quantum wave function collapse occurs upon observation, it might be said that the cat is alive and not alive at some probability until observed. It seems reasonable from the perspective of physicalist realism that the cat is not *really* in a smeared-out state of both possibilities. Until there is an observation, however, there is no way to know if the cat is alive or not. Until then, *in some sense* the cat is both alive and not at some probability.

Getting from the quantum view to the classical discrete view is said to involve the process of observing by a conscious observer. This certainly would not be expected in an objective world independent of the observer. Quantum theory not only questioned the strict cause-effect determinism of classical science, but for the first time in physics it brought in the subjective process of observing and observer as necessary parts of the scientific account of nature.

These and other implications of quantum theory deeply challenged even the most eminent scientists. Einstein, for one, argued that the theory is incomplete, though his research was instrumental in developing it. He argued that there must be unknown processes, *hidden variables*, which when eventually known will allow us to get past the indeterminate probabilism of quantum theory ('inviolable wall') and recover an objective determinate account.

As Einstein asserted, "The belief in an external world independent of the perceiving

subject is the basis of all natural science." On the issue of quantum uncertainty, he reacted: "I cannot believe that God plays dice with the universe." To the notion of wave function collapse upon observation, he quipped: "I cannot imagine that a mouse could drastically change the universe by merely looking at it (Quoted from Herbert, 1985; pp.199-210)." These comments relate directly to the quantum theory interpretations to be addressed in this paper.

The classical perspective that assumes the cat is in a *real*, discrete state whether observed or not can be associated with *physicalist realism*, sometimes also called *materialistic monism*. In this view the only *real* level of nature is the physical. But this view has not been able to account for phenomena that quantum theory and the probability wave function model accounted for quite successfully. However, orthodox quantum theory has not offered a logical explanation for how wave function collapse upon observation into a discrete physical state might occur, even asserting that the question is meaningless because there is no additional information in nature.

To add the *Wigner's friend* elaboration to Schrödinger's cat paradox, suppose we ask the friend to observe the state of the cat in the box and tell us the results. If wave function collapse requires a conscious observation, would the cat remain in *uncollapsed* probabilistic uncertainty until we observed our friend and received the report about the cat, at which point the collapse of the wave function of the cat would instantaneously occur? If so, how come our friend's observation didn't trigger a collapse?

One proposed resolution is exemplified by a quote from physicist Amit Goswami: "Quantum collapse is a process of choosing and recognizing by a conscious observer; there is ultimately only one observer (1993; p.88)." This alternative to materialistic monism is sometimes called *idealistic monism*. In this view any observation by a conscious observer collapses the wave function for all observers. The paradox arises due to assuming that our friend's consciousness and our consciousness are not one and the same.

However, there are major complications here, namely the notion of 'one' consciousness versus an observer's '*choosing and recognizing*.' In this view it is not that the 'one'



consciousness collapses the wave function, but rather ‘choosing and recognizing’ by any conscious observer. It associates wave function collapse with the conscious intention and attention of any observer. Our friend’s observation would collapse the wave function, apparently even for us if it collapses it for all observers; but we wouldn’t instantaneously know the cat’s state until we observed it, or perhaps the friend told us. Our knowledge of the cat’s state would remain uncertain and probabilistic, even though according to this view its wave function had collapsed for all observers.

But if some general form of ‘one’ consciousness collapses the wave function without ‘choosing and recognizing’ by any particular observer, wouldn’t it collapse every wave function? What would limit the ‘collapse’ of a particular quantum wave function into a particular classical object? This major issue cuts to the core of the nature of consciousness, and its relationship to individual minds. Is there a general form of consciousness throughout the universe, or is it only in individual observers? If there is a general form of consciousness not dependent on an individual observer, how come all quantum wave functions haven’t already collapsed due to it? On the other hand, if it is only related to ‘choosing and recognizing’ of individual observers, how could an individual’s observation possibly collapse the wave function for all observers?

These major issues can be viewed as requiring an expanded ontology of *real* levels of nature associated with nonlocality, addressed in a model discussed toward the end of the paper. They further bring up what actually constitutes a conscious ‘choosing and recognizing,’ as well as what degree or quality of consciousness is required to trigger quantum wave function collapse.

Considering the reasonable assumption that not only we and the friend but also the cat are conscious, wouldn’t the cat be aware of its own state of being alive, and thus would have collapsed the wave function even when we or the friend had not looked in the box? If the cat’s consciousness is one and the same with ours as well as any others, then wouldn’t it be associated with collapse of its own wave function when it was conscious?

And if so, then what happens if the cat’s consciousness is no longer capable of

collapsing the wave function because the cat expired or lost consciousness by falling asleep, but we have not yet observed it in the sense of ‘choosing and recognizing’ it? Would the cat return to an uncertain *uncollapsed* state until some other observer collapsed it, or it woke up again? Or would we just not know it collapsed, though it did collapse even in our consciousness?

More fundamentally, how could the radioactive material collapse to emit a discrete particle, the Geiger counter monitor particle decay, or the clock tick as classical measuring devices, if there are no observers to collapse the wave functions of these objects when the box is closed? Indeed, from the idealist perspective, how could there be a box, radioactive material, Geiger counter, laboratory, cat, or quantum wave function models without a conscious observer?

And this brings up another important quandary in a broader context. Consciousness is commonly assumed to require a sentient being with a classical physical brain. A conscious observer in a classical state thus seems necessary for wave function collapse, but evolved classical brains are necessary to have consciousness. How can there be classical objects such as stars, planets, galaxies, and eventually physical bodies with brains *before* any conscious mind necessary to collapse quantum wave functions into classical *reality* evolved in nature?

These questions exemplify core issues about physical *reality*, quantum processes, mind, and consciousness that need to be unpacked. But of course these examples of the Schrödinger’s cat paradox are just thought experiments for the purpose of pointing out the paradoxical nature of quantum theory. Before a *real* observation, there seems to be no way to know anything more than the probabilities known to the outside observer. And there has been at least so far no way to include an observer in the mathematical quantum wave function and also have it collapse it.

Hopefully the inconsistencies brought out by these examples hint at a different perspective that does not *objectify* quantum wave function collapse onto the physical world. In this view the ‘collapse’ refers to a change in the subjective knowledge state of the observer (*e.g.*, Hagelin, 1987; p.72), not a change in the object observed. Before



observing it, what is *real* about the state of the cat *from the observer's perspective* is that the cat is alive or not at some probability. After observing it, what is *real* about the state of the cat *from the observer's new perspective* is that the cat is in one of the two states. The observer's state of knowledge 'collapses' from probabilistic to definite upon observation, not the object (cat).

This meaning of 'collapse' as a subjective updating of knowledge in the observer would occur with an observation, whether or not the particle was emitted, and whatever happened to the cat. Whether observed or not, however, the cat would be a *real* classical object in a *real* discrete state in a *real* steel box with a *real* Geiger counter in the box, etc. Physicist Christopher Fuchs (In Folger, 2001; p.42) anticipates this view:

"When a quantum state collapses, it's not because anything is happening physically, it's simply because this little piece of the world called a person has come across some knowledge, and he updates his knowledge... So the quantum state that's being changed is just the person's knowledge of the world, it's not something existent in the world in and of itself."

This meaning of the 'collapse' as pertaining to the knowledge state of the observer and not the observed implies ontologically real quantum processes underneath the 'inviolable wall' of the physical. It is moving toward a logical understanding of how the change takes place in nature from quantum *possibilities* to physical *actualities* independent of a conscious observer.

Considering the core issues from another angle, in orthodox quantum theory the quantum wave function is an equation in imaginary mathematical space that somehow instantaneously collapses into a discrete classical object when measured or observed by a conscious observer. But the measuring device and the object that is collapsed into are classical, *real* physical objects. These classical physical objects don't have an imaginary quantum wave function in them. Also, the measuring device itself doesn't have conscious awareness, at least in the sense of what is ordinarily meant by consciousness, and thus doesn't have the ability to have the concept of a mathematical quantum wave function in it either.

So there seems to be no place where the quantum wave function exists, except somehow in the imaginary mathematical space of the conscious observer. But how could a real, discrete physical object come from imaginary mathematical space? As we unpack the orthodox model of quantum wave function collapse, it doesn't seem to address adequately ontological issues embedded in it.

When an idealized mathematical model of the quantum wave is superimposed on the wave and particle attributes of objects, it compels the conclusion that quantum wave function collapse is needed to get from the mathematical model to objects we ordinarily experience. The inner subjective updating of the knowledge associated with probability wave function 'collapse' has been *objectified* onto the outer objective world, leading to the paradoxes of the orthodox interpretation of quantum theory. This is consistent with the engrained habit throughout the history of the objective approach to proceed without considering subjectivity and mind.

Physical objects are experienced as discrete independent objects by virtue of how the ordinary senses function. When the inner cognitive functions of intellectual imagination impose a mathematical wave model onto nature, it seems to require a collapse of the wave function in order to obtain concrete classical objects. The 'collapse' is on the level of conceptions in the mind, as a reduction of mathematical possibilities and probabilities into specific states of knowledge based on new information from an observation. This meaning of 'collapse' concerns the process of knowing in the observer, not the objects being observed.

The quantum wave function can be said to be a mathematical *reality* (associated with deductive reasoning), and states of the object are a sensory *reality* (associated with inductive reasoning). The conflation of these levels has led to the measurement problem and the model of instantaneous collapse of the quantum wave function. Resolution of these issues requires an expanded ontology, which can be seen in the progress of quantum theory interpretations now discussed, in simple terms with no sense of their formal mathematical bases.

In these summaries the interpretations are reminiscent of historical attempts to address the *mind/body problem*. The



interpretations will be shown to have similarities to philosophical concepts of realism which denies the fundamental *reality* of mind, idealism which denies the fundamental *reality* of matter, and psychophysical dualism or interactionism which accepts both as *real* but didn't address how they interact. Fortunately our understanding of nature has advanced to where these issues can be addressed anew in a rigorous scientific context.

Interpretations of quantum wave function collapse

Orthodox interpretations of quantum theory have some affiliation with pragmatic and positivistic views associated with physicalist realism, but seem to be more consistent with idealism. Most adherents to these interpretations generally favored the original *Copenhagen* interpretation associated with physicists Neils Bohr and Werner Heisenberg. Others favored interpretations from mathematician John von Neumann (Herbert, 1985).

Initial orthodox (Copenhagen) interpretation

The initial orthodox interpretation emphasized quantum theory as a probabilistic model of the relationships between the actual objects in ordinary observed *reality* and the quantum concepts used to understand them. It was not an explanation of *quantum reality* because, due to the 'inviolable wall,' no explanation was believed needed or even possible. Each experiment or measurement must be taken as a whole, and an elementary particle's dynamic attributes come about through the relationship between it and the probe or measuring device, changing as this relationship changes with different observations. This was an attempt to allow for the strong evidence of quantum mechanics while still adhering to the belief that only the physical exists. It reflects how difficult the challenge was in modern physics to address the mind/matter problem directly, though the quantum model necessitated it.

In this interpretation it is fantasy to think that an individual electron is heading toward a TV screen to create a discrete blip on the screen. Before the observation or measurement associated with wave function collapse that shows up as a discrete blip on the screen, the electron has no *reality* other than

its theoretical possibility or *tendencies to exist*. If we need to imagine it as existing and traveling somewhere prior to measurement, it would be as if it were traveling everywhere in all directions, including forward and backward in time. An observation collapses the wave function to get a classical object with discrete dynamic attributes according to the experimental set-up and the measuring device.

A major concern is that practically speaking this view divides nature into two parts—discrete observed phenomena identified as *real*, and *virtual* quantum probability tendencies that apparently are not *real* objects in nature—and it did not bridge the divide. Those parts of nature not being measured, including measuring device, process of measuring or observing, and also measurer or observer, are not included because they are *real* classical objects. At least so far, specific non-probabilistic predictions about dynamic properties of classical *real* objects have not been able to be made in this quantum model.

Moreover, it impels the question of what constitutes an observation or measurement. Some have proposed that the act of making a record—a film recording, needle mark on a scroll, or any automated scoring system—counts as an observation. This suggests that wave function collapse can occur with simply a measuring device as the observer. But it is not clear what makes it a *measuring* or *observing device* on its own that compels the collapse. If any event can be said to be measured or observed (whether or not a conscious observer intending ('choosing and recognizing') to make an observation is involved, then what distinguishes an observation from events not observed?

How come all events don't involve wave function collapse, whether or not a conscious observer with intention to observe is involved? Would binoculars that are just sitting on a table, a ruler for measuring distance, a clock for measuring time, or a thermostat for temperature *create* wave function collapses on their own without conscious observers?

The physical measuring device cannot on its own sense or observe anything. And again, it doesn't have an observer with an imaginary *uncollapsed* mathematical quantum wave function in it that could collapse into another real object. As mentioned earlier, where does



the mathematical quantum wave function exist in nature to collapse if no observer is involved?

In quantum theory scientific accounts of the physical world had to address subjective issues of consciousness and mental intention. This challenge had not been addressed in objective physical science, and also seems to have remained unaddressed in the initial interpretations of quantum theory.

The all-quantum reality of von Neumann

The next interpretation to emerge, by von Neumann (1932), conceived of the entirety of nature as an undivided whole, called *quantum wholeness*. It views both quantum 'objects' and classical objects such as measuring devices as quantum processes. In this view objects remain quantum objects during and after measurement, but the possible values of the dynamic attribute being measured can be said to be squeezed down into a phenomenally experienced discrete result. In *von Neumann's proof* (1932), he showed that if electrons are ordinary classical objects with intrinsic dynamic properties of motion whether observable or not, their behavior must show differences from the probabilistic predictions of quantum theory. If quantum theory is correct, the theory that *reality* is made of ordinary classical objects is mathematically impossible according to the proof (Herbert, 1985). Curiously this seems to suggest idealism rather than realism, as if mathematical quantum processes are more *real* than physical processes. If quantum processes are in some sense *real*, then where do they exist in nature if they are not in ordinary *real* physical time and space?

In examining further the potential points from the object to the observer's consciousness to identify where wave function collapse occurs, von Neumann concluded that the only point where the collapse would have to take place is where the chain ultimately stopped, the observer's consciousness. The collapse must be somewhere and there seemed to be no other logical place for it. This identifies the crucial locus of wave function collapse as the observer's consciousness. Physicist Eugene Wigner's comment about this seems more aligned with idealism than realism:

"It is 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 (quoted in Herbert, 1985, pp.25-26)."

In von Neumann's interpretation consciousness is viewed as a separate and necessary part of nature (*Process 1*) that collapses another part which functions according to quantum mechanics (*Process 2*). These two processes interact, in some unclear way as separate while at the same time both are considered quantum processes. But we need to get to classically discrete physical causation somehow. Consciousness has to be different from quantum potentia at least in that it is said to be uniquely the site and trigger for wave function collapse.

Although emphasizing idealism and quantum *reality* more than the Copenhagen interpretation, this interpretation still has a division of quantum and classical objects. We still have two ways to account for the universe: quantum probabilistic and classical determinant equations. von Neumann intuited that something else is needed to account for the influence of consciousness on quantum and classical processes, but apparently didn't know what. This view impels further the question of what constitutes a conscious observer. What distinguishes this crucial locus of consciousness from any other random quantum process? Indeed, how can consciousness that purportedly is a product of a classical brain be a quantum process?

Many-worlds interpretation

The conclusion that objective science, especially physics, had to include consciousness was unsettling for many. Also, it seemed to require 'soft' ideas about subjectivity and conscious mind in 'hard' objective science. One prominent alternative interpretation, the *many-worlds* interpretation, can be viewed as an attempt to reestablish objectivity by eliminating the concept of quantum wave function collapse.

The many-worlds interpretation was initially developed in the 1950s through the work of physicist Hugh Everett (1957). Whereas the initial orthodox interpretation didn't acknowledge *quantum reality*, in the many-worlds interpretation uncountable quantum *realities* are generated in every



measurement act. It is sometimes viewed as an 'objective' resolution to the measurement problem in that it avoids giving special power to the process of measuring by an observer to collapse the wave function. In contrast to von Neumann's all-quantum *reality*, in the many-worlds interpretation quantum possibilities don't ever 'collapse.'

In this *no-collapse* interpretation for example, shuffling a deck of cards creates an entirely new parallel world from each possible outcome. This sometimes has been interpreted that there is a vast multitude of copies of you created every moment for each possible event outcome. But you cannot know any other uncountable versions of you that exist and multiply interminably.

Quantum theory states that a wave function represents all possible values of a 'quantum object,' superposed as mathematical probabilities. In the many-worlds interpretation, rather than collapsing into a discrete state, each possibility branches off into its own parallel world. Each world has its own particular observer, unable to experience any of the other worlds.

Sometimes taken to mean that a multitude of actual parallel worlds is created, it is perhaps better understood as a heuristic *many mind-worlds* interpretation (Zeh, 1970; Loewer and Albert, 1988). In this view superposition is taken to be at *the level of the mind*, creating an ever-expanding number of simultaneous worlds, each with its own mind associated with one of the possible outcomes. Although described as an 'objective' interpretation because it posits that the probability quantum wave function doesn't collapse upon subjective observation, it seems more like mathematical idealism, bringing subjective mind even more into the picture. There seems to be no *real* physical worlds, because wave function collapse needed for real discrete objects in nature according to the orthodox interpretation never happens. Rather than actual parallel worlds, which would violate the law of conservation of energy for example, there is one big world with many *mind-worlds* in it. New parallel worlds are created automatically, instantaneously, out of nothing, with no mechanics for their creation, and no ability to verify their existence.

How the phenomenally experienced mind-world connects with one possible event outcome is not addressed. Also, how the

observer appears to observe his or her own mind-world as a discrete world with *real* energy and mass when it is just one of infinite superposed quantum wave patterns in an *uncollapsed* mathematical quantum wave function is not addressed either. Further, the branching process that replaces wave function collapse is not defined, other than to assume it happens automatically at the instant there are possible outcomes of an event.

Even more significant, how the sense of continuous identity, the sense of 'I,' occurs in the unending branching into independent mind-worlds is not addressed. Perhaps in the other worlds there is no sense of continuity, but how do 'I' consistently end up in the special world that seems to have it? The issues about wave function collapse are hidden away in the branching of mind-worlds with no ability to know the others, producing more dilemmas than it addresses.

To summarize the trend so far, the initial interpretation conceptualized an 'inviolable wall' of indeterminism. The quantum wave function model was complete, its collapse to the *real* world was instantaneous, and there is no other information available in nature. But in analyzing how and where the collapse might take place, consciousness was reasoned to be *the* crucial locus. But then it was proposed that there is no collapse at all. Instead there is instantaneous creation of a completely new world for each possible outcome of an event. Thus the trend was toward mathematical idealism, away from physicalist realism. The next interpretation reflects a new trend that does posit quantum wave collapse, but doesn't involve a conscious observer.

Objective reduction models of wave function collapse

More recent interpretations attempt to improve upon orthodox interpretations by describing wave function collapse not clouded by the vagaries of the subjective notion of measurement. Wave function collapse is said to occur spontaneously as objects move through time, called *objective reduction*.

One version of the objective reduction interpretation is *continuous spontaneous localization*. In this version the quantum wave function evolves deterministically but contains a fundamentally probabilistic stochastic perturbation. The perturbation, insignificant in very small systems, produces wave function



collapse for large systems into localized position and other dynamic attributes typical of *real* classical, macroscopic objects. When the small stochastic perturbations add together across potential large classical objects, it becomes significant enough to cause a collapse into a discrete localized macroscopic state objectively, *on its own*. This is said to occur spontaneously in large-scale systems, without an observer.

This version reestablishes some definiteness to the world without relying on the subjective process of observing by a conscious observer. It argues for a tolerable level of indefiniteness while retaining the principle of quantum indeterminism fundamental to quantum theory, but allows discreteness in large-scale objects with no observer role in wave function collapse.

In this interpretation quantum wave collapse into classical objects takes place through interactions with the classical physical environment. Thus quantum and classical objects causally interact. If so, then importantly this implies that the quantum wave is a *real* wave of some kind, not just an imaginary mathematical description. This reflects a gigantic step toward *quantum reality*. Instead of *reality* as just the physical, or just in the mind as in idealism, objective reduction implies that both classical physical and quantum processes exist in nature; and further that the change from quantum to classical takes place through natural interactions of objects independent of a conscious observer. Numerous technological applications also support quantum processes as *real* processes in nature. This is clearly going underneath the 'inviolable wall.'

Another version of the objective reduction interpretation is the *consistent histories* approach associated with the concept of *decoherence*, which as we will see indirectly brings the observer back into the picture. Decoherence is said to be an alternative observer-independent means to assign discrete values to quantum processes (Greene, 2004). It similarly concerns interactions between an object and its environment. Objects don't exist in isolation; they exist in some environmental context. Many of the influences don't substantially change the object, but do limit its range of possibilities into a set of allowable consistent physical states.

The wave-like nature of objects is exhibited in the pattern of quantum wave interference effects. The interference effects are prominent when the wave pattern is coherent and not disrupted by environmental influences. But interactions with complex natural environments disrupt the coherence. This *decoherent* effect suppresses the quantum interference pattern. In this interpretation wave function collapse is a naturally-occurring process that is not instantaneous, occurring in *real* physical space and time, and is independent of a conscious observer. In the following quotes, Greene (2004) explains objective reduction further:

"Once environmental decoherence blurs a wave function, the exotic nature of quantum probabilities melts into the more familiar probabilities of day-to-day life... If a quantum calculation reveals that a cat, sitting in a closed box... has a 50 percent chance of being alive...decoherence suggests that the cat will *not* be in some absurd mixed state of being dead and alive... [D]ecoherence suggests that long before you open the box, the environment has already completed billions of observations that, in almost no time at all, turned all mysterious quantum probabilities into their less mysterious classical counterparts... Decoherence forces much of the weirdness of quantum physics to 'leak' from large objects since, bit by bit, the quantum weirdness is carried away by the innumerable impinging particles from the environment (pp. 210-211)."

"The wave function of a grain of dust floating in your living room, bombarded by jittering air molecules, will decohere in about a billionth of a billionth of a billionth of a billionth (10^{-36}) of a second. If the grain of dust is kept in a perfect vacuum chamber and subject only to interactions with sunlight, its wave function will decohere a bit more slowly... And if the grain of dust is floating in the darkest depths of empty space and subject only to interactions with the relic microwave photons from the big bang, its wave function will decohere in about a millionth of a second... For larger objects, decoherence happens faster still. It is no wonder that, even though ours is a quantum universe, the world around us looks like it does (p. 514)."

Objective reduction implies that quantum processes are *real* phenomena in nature. But the principle of decoherence is not sufficient alone to narrow down the phenomenal perspectives of the one world to a



consistent macroscopic outcome. There are still an unlimited number of possible observers who view the world within their own exclusive consistent perspective.

In other words, it doesn't offer a basis for determining a set of questions about the *real* world that corresponds to definite consistent answers. It also doesn't account for how different observers seem to have considerable agreement about the *real* world. It thus has similar difficulties as the 'many-worlds' interpretation with respect to how a consistent *intra-subjective* history for a particular observer is built, as well as how histories can be consistent *inter-subjectively*—continuity and consistency of experience within and across observers. This is crucial for consensual validation, a core principle not addressed in previous interpretations.

As the concept of decoherence is applied in a *consistent histories* framework, not only is context dependence of objects emphasized but also their consistent histories. The observers' experience of nature as logically consistent across events needs to be recognized as essential, even if quantum wave collapse is independent of conscious observers.

In the decoherence model some form of real quantum object 'collapses' in the sense that it reduces to a classical particle-like object through environmental interactions; and the conscious observer is out of this part of the picture. However, the perceived consistency of an object from the perspective of the observer also is necessary. The contextual environment serves as a selection process through decoherence that narrows quantum possibilities; and from the perspective of an observer these processes must be consistent. This recognizes that a conscious observer must experience consistency through time for an *empirical* science.

As a simple analogy, a sentence is constructed as a series of words with the first word setting a context that narrows down possibilities for the next. For example, if the first word is 'the,' the next word likely would be consistent with it, such as 'tree' rather than the unlikely possibility of 'however.' For another example, in the game of baseball the next consistent location for a player on first base generally is second base, depending on the context in the game as well as the initial conditions of what the game is.

The many-worlds interpretation didn't address how the world as experienced is logically related to the world in which questions requiring measurements are posed; that is, the apparent continuity within and across events. There was no continuity across the partitioning or branching of worlds.

Decoherence in a consistent histories framework concerns logical relationships between questions or measurements and definite answers or outcomes. Sets of questions are decoherent and consistent if specific answers are not superpositions of answers to other questions. Physicist and loop quantum gravity theorist Lee Smolin (2001, p. 43) explains:

"This approach lets you specify a series of questions about the history of the universe. Assuming only that the questions are consistent with one another, in the sense that the answer to one will not preclude our asking another, this approach tells us how to compute the probabilities of the different possible answers."

The outcome of measurements is a product of initial questions about the world, the observer's intentions regarding what and how to measure or observe a phenomenon (part of the 'choosing and recognizing'), and the environmental context with which objects being measured interact. Outcomes are limited to be logically consistent with the initial questions being posed, necessary for a rational experience of the world and a lawful science. In this context-dependent view there is one world with many different perspectives or minds in it. The world we get from observation depends on questions we ask, measurement choices, and environmental contexts. This is consistent with the notion of a role for the conscious observer in 'creating' the outcome of observations, but not with respect to the role of collapsing the quantum wave function. Definite answers emerge from initial questions in a context dependent manner. Smolin (2001) explains:

"It is almost as if the questions bring reality into being. If one does not first ask for a history of the world that includes the question of whether dinosaurs roamed the Earth a hundred million years ago, one may not get a description in which the notion of dinosaurs—or any big 'classical objects'—has any meaning (p. 44)."

In this view there is one world with many consistent decoherent histories of it that



are brought into being independently, via many different conscious observers. Still, in this interpretation *reality* remains on the level of an unlimited number of possible observers. Smolin (2001, p. 44) further states:

“Each history is incompatible with the others, in the sense that they cannot be experienced together by observers like ourselves. But each is, according to formalism, equally real... Either quantum mechanics is wrong when applied to the whole universe, or it is incomplete in that it must be supplemented by a theory of which set of questions corresponds to reality...”

Another major implication of this view is that the basis for consistent histories is the *initial conditions*. Subsequent events are sensed as following initial events in a logical sequence. The entire history of the universe that gives consistent answers needs to be consistent with the initial conditions. This point also fits the notion of an overall asymmetric direction to time—*arrow of time*—fundamental to how infinite possibilities manifest as discrete phenomena. It is further consistent with the second law of thermodynamics which holds that nature tends toward increasing entropy. These widely accepted principles have not been integrated fully into either classical or quantum theories. The principles imply that the initial conditions include all possible consistent answers to questions about nature, which suggests initial order.

The context-dependent principle of decoherence and objective reduction differ significantly from the model of quantum wave collapse in orthodox interpretations. If the quantum wave causally interacts with the *real* physical environment and decoheres through this interaction, it certainly is not just an imaginary conception in mental space, not just a mathematical function, and not just random quantum potentia. Objective reduction implies a distinction between an ontologically real nonlocal quantum wave and the probability wave *function* in the observer's *mental space*, both different from objects in physical space.

But also, it recognizes that a conscious observer with a frame of reference must be involved for consistent histories of the universe. Even further, such consistency applies both intra-subjectively (within) and inter-subjectively (across) observers. It is required for any consensually agreed-upon

understanding and experience of nature as orderly and lawful.

The trend in these more recent interpretations of quantum theory is toward objective interaction of quantum *reality* and physical *reality*, with the subjective conscious observer having no direct role in quantum wave collapse. But also the observer is becoming recognized as fundamental for a logically consistent empirical science.

However, we don't yet have a model of a *real* conscious mind, and we don't yet have a model of a conscious observer with mental intentions of 'choosing and recognizing' that can actually change the causal chain of events. We still have not bridged the gap between idealism and realism, subjective observer and objective observed, mind and matter. In the following quote, mathematician and cosmologist Sir Roger Penrose (2005; pp.1031-1032) discusses many of the core issues in the above discussion of models of quantum wave function collapse:

“In fact, almost all the 'conventional' interpretations of quantum mechanics ultimately depend upon the presence of a 'perceiving being', and therefore seem to require that we know what a perceiving being actually is! We recall that the Copenhagen interpretation...takes the wavefunction not to be an objectively real physical entity but, in effect, to be something whose existence is 'in the observer's mind.' Moreover, at least in one of its manifestations, this interpretation requires that a measurement be an 'observation,' which presumably means something ultimately observed by a conscious being—although at a more practical level of applicability, the measurement is something carried out by a 'classical' measuring apparatus. This dependence upon a classical apparatus is only a stopgap, however, since any actual piece of apparatus is still made of quantum constituents, and it would not actually behave classically—even approximately—if it adhered to the standard quantum...evolution.... The issue of environmental decoherence...also provides us with merely a stopgap position, since the inaccessibility of the information 'lost in the environment' doesn't mean that it *actually* is lost, in an objective sense. But for the loss to be subjective, we are again thrown back on the issue of 'subjectively perceived—by whom?' which returns us to the conscious-observer question.... The many-worlds description of reality is manifestly dependent



upon having a proper understanding of what constitutes a 'conscious observer', since each perceived 'reality' is associated with an 'observer state', so we do not know what reality states (i.e., worlds) are allowed until we know what observer states are allowed. Put another way, the behavior of the seemingly objective world that is actually perceived depends upon how one's consciousness threads its way through the myriads of quantum-superposed alternatives. In the absence of an adequate theory of conscious observers, the many-worlds interpretation must necessarily remain fundamentally incomplete.... The consistent histories approach...is also explicitly dependent upon some notion of what 'an observer' might be.... As far as I can make out, the only interpretations that do *not* necessarily depend upon some notion of 'conscious observer' are that of de-Broglie-Bohm...and most of those...require some fundamental change in the rules of quantum mechanics.... I am an adherent of this last view... Accordingly, there is no need to invoke any conscious observer in order to achieve the reduction of the quantum state...when a measurement takes place."

Objective reduction interpretations imply *quantum reality* in addition to physical *reality*. When unpacked a little further, however, additional questions arise. The collapse to a classical physical object independent of the observer means that no quantum wave function as an imaginary mathematical model of nature is involved. The object that decoheres, such as a grain of dust as described in the earlier quote from Greene (2004), presumably has no ability to imagine or model anything because it has no brain or conscious mind in it. If no observer is involved, then there is no quantum wave function involved either. Then what decoheres?

The conclusion seems to be that it is some abstract but *real* 'quantum objects' that decoheres through interactions with the physical environment. The collapse would be of a *real*, coherent quantum wave rather than a quantum wave *function* in imaginary mathematical space. But then again, on the other hand, how could a 'quantum object' theorized to spread throughout the unbounded quantum field interact with the classical environment?

These points strongly suggest that there is some yet to be defined process that allows this *real* but abstract, intangible unbounded

wave pattern made of quantum wave fluctuations to interact causally with physical objects in ordinary space and time that makes it decohere. Consistent with Greene's (2004) description, decoherence occurs so rapidly and at such small distance scales that an ordinary observer could not see it even if it happened to occur while an observer is looking at the location where the object appears when it decoheres. But it doesn't make sense that the 'decohering' object just pops into physical existence so that it is capable of being observed or measured *without any precedents*.

In other words, there needs to be causal mechanisms that bridge through the 'inviolable wall.' The environment that makes the quantum wave decohere is already composed of ordinary physical objects such as, in the case of a grain of dust, air molecules, sunlight, the microwave background, other grains of dust, and other influences. These physical objects themselves also must be fluctuations of quantum fields that continue to exist whether the particular quantum object decoheres or not.

So it would seem that the quantum level of these objects, as well as the quantum level of what becomes a grain of dust, exists in some sense as *real* even before 'decohering' into physical objects. This notion of a 'collapse' would then be the natural change of *real* quantum waves in a coherent state to the predominance of a *real*, decoherent particle state. The rate of collapse would depend on random activity in the environment that interacts with the quantum wave. But it would decohere prior to and independent of an observation. This type of 'collapse' would be of a *real* quantum wave via objective reduction independent of an observer.

As mentioned earlier, however, the 'collapse' of the imaginary mathematical quantum wave probability *function* would then refer to a change in the subjective knowledge state of the observer due to observing the already 'decohered' physical object. With an observation, the observer updates his or her knowledge about the object, whether a grain of dust or a cat. This means for example that the cat in the steel box is a *real* object whether observed or not. This unpacks the conscious observer from *real* quantum waves and *real* physical objects.



But the important question whether the conscious mind of the observer is *real* has not yet been addressed. The next model proposes *real* conscious minds, a logically necessary step in order for mind and matter to link together and causally affect each other. It certainly doesn't seem logical that non-real imaginary objects would have causal links with *real* physical objects. This next model proposes how *real* conscious minds have causal power over matter.

Neorealist interpretation of quantum wave collapse

The final interpretation outlined here, noted in the Penrose quote above, is associated with mathematician and physicist David Bohm. It incorporates principles somewhat similar to decoherence to explain the probabilism of motion contributing to wave-particle effects, but doesn't attribute the cause of quantum wave collapse to conscious observation.

This interpretation has been labeled *neorealism* because of its renewed emphasis on determinism. Importantly, however, it includes both physical *reality* and quantum *reality*, not only physical realism as a materialistic monism. It takes *quantum reality* implied by objective reduction much further, explicitly positing an ontologically *real* level underlying the physical world that is associated with *real* conscious minds.

Reference was made earlier to *von Neumann's proof*, which argued that discrete objective *reality* cannot exist in the way it is ordinarily understood if quantum theory is correct. This had the effect of placing much of the work on the nature of *reality* as investigated in theoretical physics on hold for decades. In the 1950s, however, an interpretation was put forth by Bohm that seemed to defy the proof.

This new interpretation provided a mathematical model of elementary particles as *real* classical objects with intrinsic dynamic attributes that matched the probabilistic predictions of quantum theory. It can be described as a realization of Einstein's 'hidden variables' critique of quantum theory, perhaps in part influenced by conversations the elderly Einstein had with Bohm. Largely ignored for years, it is now receiving renewed interest (Talbot, 1991, Goldstein, 1998). Although as with other quantum models such as string theory for example the detailed mathematics

has not been worked through, its core principles are viewed as significant advances in addressing paradoxes in the quantum model of nature.

This interpretation is described as a deterministic reformulation of quantum theory within an objective perspective (Talbot, 1991). Quite importantly the notions of objectivity as independent of the subjective observer and causal determinism rather than fundamental quantum indeterminism are both *recovered*, but not in their classical forms.

It is a mathematical theory of the motion of particles in which the path of a *real* elementary particle is guided by a *real* nonlocal wave. In this interpretation atoms are *real* classical objects; and the underlying waves are also *real* but are a more abstract, subtler level of nature. The underlying wave field is nonlocal and beyond the conventional level of ordinary spacetime. It is an underlying, deterministic, causally efficacious nonlocal field that permeates the physical.

"[G]rowing dissatisfaction with several of the other prevailing views in physics caused Bohm to become increasingly troubled with Bohr's interpretation of quantum theory.... [W]riting a textbook...he still wasn't satisfied...and sent copies of the book to both Bohr and Einstein.... [In] a six-month series of spirited conversations, Einstein...admitted he was still every bit as dissatisfied with the theory as was Bohm.... Bohr and his followers...claimed that quantum theory was complete and it was not possible to arrive at any clearer understanding.... This was the same as saying there was no deeper reality beyond the subatomic landscape, no further answers to be found.... Inspired by his interactions with Einstein, he [Bohm] accepted the validity of his misgivings about quantum physics and decided there had to be an alternative view... He began by assuming that particles such as electrons *do* exist in the absence of observers. He also assumed that there was a deeper reality beneath Bohr's inviolable wall.... [B]y proposing the existence of a new kind of field on this subquantum level he was able to explain the findings of quantum physics as well as Bohr could. Bohm called his proposed new field the *quantum potential* and theorized that, like gravity, it pervaded all of space. However, unlike gravitational fields, magnetic fields, and so on, its influence did not diminish with distance (Talbot, 1991, p. 39)."



This neorealist interpretation is sometimes referred to as the most successful interpretation of non-relativistic quantum theory because it provides a reasonable solution to the paradoxes of the measurement problem and instantaneous quantum wave function collapse (Dickson, 1998). However, it does this through an approach considered quite radical in that it explicitly posits an ontological level of nature underlying the ordinary *real* physical world that causally guides it.

In direct contrast to the orthodox interpretation, it holds that quantum objects are not all the same but are intrinsically different, and that their dynamic attributes exist independent of the observer in the objects themselves, hidden when not classically measured. It posits that the wave function gives a probabilistic description of a group of quantum objects, but is an incomplete description of an individual quantum object. A single quantum object is unpredictable due to *classical* uncertainty (deterministic but unspecifiable). In this interpretation, orthodox quantum theory is incomplete, as Einstein asserted.

In this interpretation *reality* is the same whether measured or not. For example electrons are particles when measured as well as when not being measured. Their dynamic attributes of motion are directed by a *real* but extremely abstract *guiding wave*, *pilot wave*, or *psi wave*, also called the *quantum potential*.

To match the behavior of objects according to quantum probability predictions, this psi wave must be connected to every particle in the universe, classically invisible, superluminal, and a common aspect of nature (Bohm, 1980). It is a more fundamental medium not limited by Einstein locality and causality.

The notion of wave function collapse is accounted for in terms similar to decoherence and the apparent destruction of wave interference patterns when impacted by another system in the environment, including a measurement probe of some kind. The wave aspect is the guiding or psi wave, and it doesn't collapse into a particle object upon observation. It guides the elementary particle, such as an electron or photon, along its path.

It is the wave nature of the psi wave that produces the appearance of wave patterns such as interference effects. The path of a particle is determined by the psi wave and also the myriad of mechanical electric, magnetic, and gravitational effects of the known fundamental forces that comprise the entire experimental arrangement and measurement process. This interpretation accepts the world as a seamless, inseparable whole, akin to quantum wholeness as in orthodox interpretations. It also adds that the observation dissolves the separation of observed and process of observing. Bohm (1980; p.18) emphasizes that:

“One is led to a new notion of unbroken wholeness which denies the classical analyzability of the world into separately and independently existing parts... The inseparable quantum interconnectedness of the whole universe is the fundamental reality...”

This interpretation offers a deterministic account of quantum probabilities as arising from averaging over initial unknown random conditions, rather than from an inherent ‘inviolable’ indeterminism. The path of an elementary particle is deterministic in its dynamic attributes such as position and momentum. Its path is a combination of the influence of the quantum potential or psi wave and the myriad of other specified and unspecified deterministic contextual influences that make up the whole experimental arrangement. Together these changing influences produce a fuzzy, jittery, complex path of motion. Because the psi wave is nonlocal, doesn't drop off with distance, and is highly interconnected, influences that make up the entire experimental arrangement must include about everything in the universe. They are so complex and entangled as to be *unfathomable*; thus the particle's path is not precisely predictable.

Also it is in the sense that all components of the experimental set-up influence the process of measurement that they can be said to *create* discrete classical *reality*. Any change in the experimental arrangement would result in a different outcome. This gives an explanation for the process of observation creating the outcome objectively within a framework of causal determinism and realism. With respect to this aspect of the interpretation, the subjective



conscious observer does not have a role (Bohm, 1980).

It further provides an explanation within the framework of determinism and realism for quantum wholeness in the sense of nonlocality, exemplified by phase entanglement in which distant objects interact superluminally. The experimental verification of nonlocality did not, and could not within its ontological limitations; explain the mechanism through which phase entanglement is mediated. This interpretation posits such a mechanism in the psi wave or quantum potential.

The psi wave carries information in that it sensitively reflects the totality of the experimental arrangement. It represents 'active information' (Bohm & Hiley, 1993) through which it guides particle motion, but not through the strength of the ordinary forces involved. The path of particles is influenced by the fundamental forces on the gross physical level that shape the complex physical environment. But is it also possible to guide particles from information in the psi wave, such as through subtle mental intentions?

It is in trying to account for this possibility that this interpretation also brings the conscious observer into the picture. Bohm has speculated that the nonlocal mind of a conscious observer may operate with extreme subtlety to allow such sensitive but systematic information transmission. He has proposed this as a general framework for how mind influences matter (Bohm, 1980). The psi wave may be related to extremely subtle intentional action on an underlying nonlocal level of mind (Goldstein, 1998).

Elaborations of this interpretation expand the concept of the psi wave to a subtle, nonlocal, non-linear field that constantly enfolds and unfolds, and in which any local region of space is interconnected nonlocally with the entire universe. Nature is viewed as a single wholeness or totality enfolded in each individual region of space—somewhat akin to holographic models. In the following quote Bohm and his colleague physicist B. J. Hiley (1993, pp.385-386) summarize how the undivided wholeness relates to physical and mental phenomena, associated with what they have identified as the *implicate order*:

"One may then ask what is the relationship between the physical and the mental

processes? The answer that we propose is that there are not two processes. Rather, it is suggested that both are essentially the same. This means that that which we experience as mind, in its movement through various levels of subtlety, will, in a natural way ultimately move the body by reaching the level of the quantum potential and of the 'dance' of the particles. There is no unbridgeable gap or barrier between any of these levels. Rather, at each stage some kind of information is the bridge. This implies that the quantum potential acting on atomic particles, for example, represents only one stage in the process... It is thus implied that in some sense a rudimentary mind-like quality is present even at the level of particle physics, and that as we go to subtler levels, this mind-like quality becomes stronger and more developed."

This view proposes two levels that make up the one wholeness. Both are causally determinate, interconnected, and interacting with each other but with different properties associated with different levels of *reality* or domains of existence. The surface classical level—*explicate order*—is the familiar world of mechanical particle interactions mediated by the four fundamental forces within Einstein locality and light-speed. The subtler level—*implicate order*—is a highly interconnected, enfolded *reality* of nonlocal interactions more of the nature of mind and abstract thought waves than matter particles.

This finally brings into the natural world and its causal chain the causal efficacy of *real* conscious observers. It is not, however, a return to the classical deterministic model of causality. It rather hints at a new form of causality suggested by nonlocality, in which space and time are more interconnected.

As a simple analogy, the physical universe can be likened to an iceberg in the unbounded ocean. The iceberg is a more restricted or solid state with its own emergent properties, but basically is made of water. The waves and currents in the water move the iceberg around in the ocean. The environment inside the iceberg is different from the outside water, but emerges from and is nothing other than water. The iceberg world is a more restricted, less dynamic level than the ocean of water from which it is built.

On the subtle level of nature, causality can be viewed as more wave-like, not particle interaction-like. It is a more abstract fabric of



spacetime than the relativistic spacetime gravitational field, with more abstract causal dynamics. Although we ordinarily sense events in physical space and time as discrete, we also have an intuitive sense of the unseen converging precedents that causally shape events. And as well we have some sense of the continuing aftereffects of the perceived discrete event that shape subsequent processes and events.

All these influences can be pictured in terms of a *causal wave* that is more spread out in an underlying medium of spacetime, with the gross field embedded in and emerging from this more abstract, encompassing, and extended subtle field. This means that there is information in the subtle causal wave shaping upcoming events that precedes the ordinary information we associate with these discrete events in the causal nexus of ordinary spacetime. It can be viewed as somewhat analogous to the relativistic concept of 'time dilation,' in which time spreads out, so to speak, and in which aspects of an event wave precede the discrete view of causality. It entails nonlocal causal determinism outside of Einstein local causality in a wider angle view.

In this perspective discrete events in ordinary space and time can be described as also being encompassed in a subtler level of existence underlying it. This subtler level is less localized than discrete ordinary space and time. Causation is spread out in waves of a subtler medium of nonlocal space-time, permeating the more concrete gross level of space-time where sensory objects are experienced as independent and localized with causation modeled in terms of classical 'billiard ball' mechanics.

This more abstract level of nature allows for new ways to address major quandaries in classical physical realism about mind and consciousness. In this expanded ontology the theorized closed physical causal chain does not mysteriously unlink to insert an emergent conscious mind at some stage of evolutionary neural complexity, and the conscious observer is not epiphenomenal or powerless as in physical realism. Rather, the mind of an individual conscious observer is nonlocal, and it influences physical events via the underlying psi wave. The implicate order that includes mental space permeates matter, and causally guides it.

This view of an implicate order reflects further unpacking of physical *reality* from an unmediated instantaneous collapse of the quantum wave function. It is quite distinct from Einstein's relativistic spacetime gravitational theory, though attempting to account for phenomena explained by both quantum and relativity theories. Bohm and Hiley (1993; pp.347-348) describe this proposed deeper level as a *sub-relativistic* level of nature:

"[W]e say that underlying the level in which relativity is valid there is a subrelativistic level in which it is not valid even though relativity is recovered in a suitable statistical approximation as well as in the large scale manifest world.... Although there is no inherent limitation to the speed of transmission of impulses in this subrelativistic level, it is quite possible that the quantum nonlocal connections might be propagated, not at infinite speeds, but at speeds very much greater than the speed of light.... As the atomic free path quantum indeterminacy or randomness is the first sign of a subcontinuous' domain in which the laws of continuous matter would break down at the quantum level, so the free path in our trajectories would be the first sign of a subquantum domain in which the laws of quantum theory would break down.... The next sign of a breakdown of the quantum theory would be the discovery of some yet smaller dimension whose role might be analogous to the dimension of an atom in the atomic explanation of continuous matter [the classical microscopic level]. We do not as yet know what this dimension is, but it seems reasonable to propose that it could be of the order of the Planck length, where, in any case, we can expect that our current ideas of space-time and quantum theory might well break down."

Bohm (1980, p. 235) further describes how the implicate order causally relates to the physical level:

"So we are suggesting that it is the implicate order that is autonomously active while... the explicate order flows out of a law of the implicate order, so that it is secondary, derivative, and appropriate only in certain limited contexts. Or, to put it another way, the relationships constituting the fundamental law are between the enfolded structures that interweave and interpenetrate each other, throughout the whole of space, rather than between the abstracted and separated forms that are manifest to the senses (and to our



instruments).”

We still seem to have two basic equations to describe nature: the classical equations and now the psi wave equation. However, the model emphasizes the seamless interrelationship of the two domains or levels. Bohm (1980) describes the explicate order as permeated by the implicate order, both arising from the universal flux, plenum, or ‘super-implicate order.’

“Our proposal to start with the implicate order as basic, then, means that what is primary, independently existent, and universal has to be expressed in terms of the implicate order. So we are suggesting that it is the implicate order that is autonomously active while...the explicate order flows out of a law of the implicate order, so that it is secondary, derivative, and appropriate only in certain limited contexts. Or, to put it another way, the relationships constituting the fundamental law are between the enfolded structures that interweave and interpenetrate each other, throughout the whole of space, rather than between the abstracted and separated forms that are manifest to the senses (and to our instruments) (p. 235).”

“[T]here is a universal flux that cannot be defined explicitly but which can be known only implicitly, as indicated by the explicitly definable forms and shapes, some stable and some unstable, that can be abstracted from the universal flux. In this flow, mind and matter are not separate substances. Rather, they are different aspects of one whole and unbroken movement. In this way, we are able to look on all aspects of existence as not divided from each other, and thus we can bring to an end the fragmentation implicit in the current attitude toward the atomic point of view, which leads us to divide everything from everything in a thoroughgoing way (p. 14).”

Though specifying the two levels, explicate and implicate orders, this interpretation is not psychophysical dualism. It emphasizes causal seamlessness between these two levels, as well as quantum wholeness in which the more expressed classical explicate order is a grosser manifestation of the subtler, more encompassing implicate order. And both exist within an ultimate universal plenum or *super-implicate order*. It is thus a non-dual or monistic account.

Another recent model of three levels of nature has been proposed by physicist Henry

Stapp (2000; 2007). In the following quotes about quantum wave function collapse, a three-level model is evident. Stapp (2000) states that consciousness is needed in wave function collapse because:

“...the local-reductionistic laws of physics, regarded as a causal description of nature, are incomplete.... The physical part of reality represents merely the possibilities for an actual experience, not the actually experienced reality itself.”

[F]rom the purely physical standpoint the [wave function] collapse seems to come from nowhere, as an unpredictable and undetermined ‘bolt from the blue.’ Something is needed to...bring ‘classicality’ into the dynamics, and it needs a ‘cause’ for the collapse, and it needs a reality to complement the ‘potentia’... It must be something that exists, and the only thing that we know exists; besides the physical part of reality...is the experiential part... (p. 213).”

This model identifies three *realities*: quantum possibilities in Hilbert space, the physical, and the experiential. The concept of all-inclusive Hilbert space as used in Stapp’s model has similarities with the concept of the universal plenum or super-implicate order in Bohm’s neorealist interpretation of quantum theory, it also has affinity with the emerging theory of the unified field as the source of everything.

And further, it has similarities with the ‘Platonic realm’ in a model proposed by Penrose (2005, pp. 17-23). In a discussion of abstract mathematical forms associated with a *Platonic realm* in nature, Penrose states:

“I am aware that there will still be many readers who find difficulty with assigning any kind of actual existence to mathematical structures. Let me make the request of such readers that they merely broaden their notion of what the term ‘existence’ can mean to them. The mathematical forms of Plato’s world clearly do not have the same kind of existence as do ordinary physical objects such as tables and chairs... Objective mathematical notions must be thought of as timeless entities and are not to be regarded as being conjured into existence at the moment that they are first humanly perceived... Those designs were already ‘in existence’ since the beginning of time, in the potential timeless sense that they would necessarily be revealed precisely in the form that we perceive them today, no matter at what time or in what location some



perceiving being might have chosen to examine them... Thus, mathematical existence is different from physical existence but also from an existence that is assigned by our mental perceptions. Yet there is a deep and mysterious connection with each of those other two forms of existence: the physical and the mental... I have schematically indicated all of these three forms of existence—the physical, the mental, and the Platonic mathematical—as entities belonging to three separate ‘worlds’... There may be a sense in which the three worlds are not separate at all, but merely reflect, individually, aspects of a deeper truth about the world as a whole of which we have little conception at the present time.”

An additional three-level model, emphasizing the unified field-based perspective, has been proposed by physicist and unified field theorist John Hagelin (1989). This approach utilizes the abstract mathematical *Lagrangian* formulation. In very compact form, the Lagrangian contains two terms. The first term, denoted as *phi*, can be described as a classical conception of a static space and time translation invariant field—a non-changing field of *existence*. The second term represents orderly dynamism or change, denoted as *II*. This term can be thought of as representing the inherent capability of the field to generate orderly change in the field. Hagelin (1989) associates it with the most abstract interpretation of the *quantum principle*:

“The precise mathematical structure of the unified field serves as an unmanifest blueprint for the entire creation: all the laws of nature governing physics at every scale are just partial reflections or derivatives of this basic mathematical structure. However, this view of intelligence in terms of the classical symmetries of the unified field is a rather passive and inert one. The term ‘intelligence’ achieves its full significance only at the quantum-mechanical level of description, in which the field acquires a degree of *dynamism, discrimination and creativity* not present at the classical level (p. 9).”

The Lagrangian formulation places the unified quantum field in Hilbert space, a complex vector space of infinite dimensions—an infinite collection of points that comprise all states of a quantum mechanical system. Hagelin (1989) uses the Lagrangian formulation in Hilbert space to present a unified field theory that more explicitly includes principles identifiable with the

concepts of the knower or observer and the process of knowing, not merely the known.

The *knower* or observer quality of the field is interpreted as the property of the Hilbert *space* of states to be a non-changing, unmanifest background for all possible unitary transformations or states of the field, while itself remaining completely unchanged. It is the uninvolved ‘observer’ of all transformations that, through its dynamic orderliness associated with the discriminative role of the inner product in evolving the quantum mechanical system, determines the physical manifestations of the system. The *process of knowing* quality of the field is related to quantum mechanical *observables* that serve as quantum mechanical operators in Hilbert space, generating changes of one state into another in unitary transformations. The *known* is interpreted as the stable quantum mechanical *states* themselves.

Thus this model incorporates from a mathematical perspective the three aspects of knower or observer, process of observing, and observed. The observer is related to Hilbert *space*, the process of observing to the quantum mechanical *observables*, and the observer to the quantum mechanical *states*.

Each of the above models proposes three fundamental levels or domains of nature. Penrose (2005, pp. 17-23) asserts that “we have little conception at the present time” about the domains underlying the physical level, and Bohm and Hiley (1993) made a similar comment. But a three-level model is articulated extensively in Vedic literature (Maharishi, 1963; Hagelin, 1989).

Unified field theory posits an abstract super-symmetric field that underlies all phenomenal existence and that undergoes spontaneous symmetry-breaking into the four fundamental fields of nature. It can be said conceptually to bring everything down to a single framework, exemplified for example in the concept of the Lagrangian—which when elaborated allows for both quantum and classical processes. How unified field theory might incorporate consciousness and the subjective is beyond the scope of this paper (see Hagelin, 1987; Boyer, 2010). But the ancient Vedic view of how the unmanifest transcendent source of nature manifests into phenomenal *reality* appears to have a deep correspondence with it. Because this ancient view focuses on consciousness and the



subjective observer, it is quite relevant to this discussion of the role of conscious mind with respect to quantum wave collapse.

According to the ancient Vedic tradition, as well as other ancient traditions albeit with various cultural and language differences, there is a transcendent universal essence of nature. Most of these ancient traditions further hold that direct experience of the transcendent universal essence of nature is possible. It is said to be possible because the universal essence of nature also is held to be the essence of one's own consciousness—universal *Being* as the essence of individual being, universal consciousness as the essence of individual consciousness.

This completely holistic view is outlined in the *Sankhya* aspect of Vedic literature, which refers to 'enumeration' of the number of levels of nature, Sankhya identifies levels said to range from the all-encompassing universal Being or unified field to the grossest level of rocks and earth. It is depicted in the three-level model of the gross, the subtle, and the transcendent in the diagram (Table 1) below. Vedic terms are added in parentheses.

Gross/local [manifest]	Gross sensory environment Gross macroscopic brain/body Electrochemical cellular processes Atomic/sub-atomic particle processes (Mahabhutas)
Subtle/ nonlocal [manifest]	Subtle wave processes (Tanmatras) Subtle organs of sense/action (Gyanendriyas/Karmendriyas) Mind (Manas) Intellect (Ahamkara) Holistic self or ego (Mahat)
Unified field [unmanifest]	Universal Being (Prakriti/Purusha)

Table 1. An interpretation of the 3-in-1 Sankhya model of levels of nature in Vedic literature, with the gross local level embedded in and permeated by the subtle nonlocal level, which in turn is embedded in and ultimately nothing other than the transcendent unified field or universal *Being*.

In the completely holistic Vedic account the unified field can be understood to be universal Being, the underlying essence of consciousness itself. In this view each of the levels of nature is a cosmic level that includes individual levels. Thus universal Being or universal consciousness has within it individual being or individual consciousness.

Further, the levels of cosmic ego, intellect, and mind have within them corresponding levels in individual sentient beings. This can be likened to how individual physical objects are embedded in the spacetime gravitational field.

From within the infinite unified field of universal *Being*, finite levels are expressed with increasing limitations from subtlest to grossest. Individual minds and individual objects of sense—the subject-object duality—also emerge with increasing expressions of limitation and concreteness from the subtlest to the grossest levels. This three-level model is ontologically rich enough to resolve fundamental issues of the relationship of mind and matter that underlie the paradoxes associated with quantum theory and the model of quantum wave function collapse.

An overriding issue has been emerging that contrasts the view of the cosmos in terms of locality, captured in the concepts of Einstein locality and the light cone in relativity theory, with entangled nonlocality associated with the concept of *holism* in quantum theory. Bohr's undivided wholeness of the experimental arrangement, von Neumann's quantum wholeness or all-quantum *reality*, the principle of nonlocality, and Bohm's psi wave and implicate order represent steps toward a more interconnected, nonlocal model of the universe.

Historically modern scientific methodology hinged on the assumption of the independence of objects in nature (refer to Einstein's quote at the beginning of this paper). These cutting edge three-level models are in the direction of suggesting that the object independence on the surface of nature is underlain by increasing interdependence at deeper levels. And from the holistic perspective, all things are connected and nothing is completely independent. Holism implies that the independence of objects, objective reality, and subject-object duality are conditional or contextual views of *reality* with limited range of application.

Herein is a major concern relevant to interpretations of quantum theory, orthodox as well as non-orthodox, and also relativity theory. The model of quantum wave collapse throughout the unbounded quantum field implies nonlocality and holism. For the most part the classical view including Einstein relativity theory implies locality. These two fundamental views of nature have not yet been



integrated. This directly concerns integrating quantum and relativity theories into quantum gravity (unifying fermions and bosons), widely acknowledged as a necessary step toward a viable unified field theory.

In addressing the measurement problem, quantum wave collapse, and the mind-body problem, contemporary models are starting to posit not two but rather three ontological levels or domains of nature. Whereas materialistic monism posited only physical *reality*, these more recent views posit one ultimate *reality* (unified field) that contains subtle nonlocal and gross local levels.

This three-level ontology points toward a possible reconciliation to the fundamental issues of locality vs. nonlocality, reductivism vs. holism, and the mind-body problem. This trinity also appears in various forms as a theme in many religions and other worldviews. Ultimate integration of the three-level model of nature is articulated in great detail in the ancient Vedic tradition of knowledge, as the *three-in-one* structure of nature. This holistic approach has been interpreted in the modern scientific context and language by Maharishi Mahesh Yogi as *Maharishi Vedic Science and Technology*.

Conclusion

The ancient Vedic model holds that there is an infinite self-interacting holistic unified field, within which is the subtle nonlocal interdependent level, which permeates the gross local independent level. It identifies nonlocal and local aspects of nature as existing apart from any individual observer. This 3-in-1 model of levels of nature is used in the concluding summary to address key issues in this paper.

Do objects exist independent of the process of observing and the observer?

In the Sankhya model the duality of subject and object fundamental to classical science emerges at the subtle nonlocal level of cosmic intellect. At the subtle level of nature, there is a separation into universal mind including individual minds (Manas) with sensory ability to experience objects (Indriyas) and the subtle objects of experience (Tanmatras). This subject-object separation associated with independence of objects and with particle interaction causality (Mahabhutas) is much

more predominant on the ordinary gross physical level of nature.

Thus in this model there are objects in nature that can be said to be independent of the process of observing and any individual observer on both subtle and gross levels of nature, which supports realism and fundamental objectivity. On the other hand, idealism and fundamental subjectivity are also supported in that what the independent world appears to be depends on the subjective observers.

Both of these *real* levels are conditional because ultimately all objects and observers, all objectivity and subjectivity, remain within the infinitely self-interacting unified field or universal Being (Prakriti/Purusha). Objects do exist relatively independent of individual subjective minds, but not independent of universal *Being* or the all-encompassing unified field.

Is there a level of quantum reality in nature?

Quantum *reality* would mean that quantum objects are ontologically *real* objects in nature, and Sankhya supports this view as a conditional *reality*. Quantum objects are not physical in the sense of being composed of classical particles localized within ordinary relativistic spacetime within light-speed. They are *real* nonlocal objects, for the most part associated with the Tanmatras, the subtle objects of nature according to Sankhya.

Is there a nonlocal field not mediated by the four known fundamental local forces?

Yes, this ontologically *real* subtle level, medium, or field of nature does not have the limitations that characterize the four known local forces (gravitational, strong and weak nuclear, electromagnetic), at least as ordinarily understood. Nonlocal processes in the subtle level are associated with the Tanmatras, which can be said to be entangled and interdependent. Going from subtler to grosser levels, the more interdependent wave nature of objects is suppressed or hidden and the more discrete, independent particle nature of objects becomes more prominent. In other words, reductive parts rather than underlying wholeness become more apparent from the transcendent to the subtle and then to the gross level.



Is superluminal communication possible?

As depicted in Table 1, the subtle nonlocal level includes the subtle objects of sense (Tanmatras), the subtle senses (Gyanendriyas, and also Karmendriyas), and the levels of mind (Manas, Ahankara, Mahat). Processes at this level are entangled and their interactions are not limited to ordinary space and time and the speed of light. In this view superluminal communication is how mind naturally influences matter. At the gross local level of nature, change is via particle interaction mechanics within the speed of light. At the subtle nonlocal level, it is via nonlocal wave dynamics that can be superluminal but are not instantaneous. At the level of the infinitely self-interacting unified field, it can be said to be instantaneous—that is, beyond both the ordinary gross independent and subtle interdependent levels of spacetime—*infinitely self-interacting*.

Are causally efficacious conscious intentions and free will real?

Yes. In Sankhya the subtle domain (implicate order) is where individual conscious minds exist as nonlocal phenomena. Individual minds are underneath and permeate local physical body/brain processes; and conscious intentions are subtle impulses that drive the subtle and gross organs of action in the body and brain according to the free choices of the individual observer. In other words, individual subjective minds impel changes in phenomenally *real* inert matter via subtle thought waves of *real* mental intentions—mind over matter. It is important to point out that nonlocal mind does not mean that it cannot be identified as individual mind. It does not mean group mind with no individuality.

Is nature fundamentally indeterminate or determinate even if unfathomable?

Nature is determinate, not random and indeterminate (though random processes may be involved on some levels). Causation does not end at the ‘inviolable’ quantum level such that quantum indeterminism takes over entirely. But in this view causation is not just the discrete ‘billiard ball’ particle interaction model. At the subtle level, causation is more wave-like than particle-like, expanded into a more abstract, wider-angle, interdependent

medium or domain of space, time, and causality. It can be envisioned as somewhat analogous to the notion of spacetime dilation in relativity theory, but not with respect to ordinary spacetime. The determinism is so entangled and complex that it is probabilistic rather than precisely calculable, as in classical determinism.

Is there is a collapse of the quantum wave function?

There is no quantum wave collapse in the orthodox sense that it occurs instantaneously via conscious observation. Also, there is no quantum wave collapse in the sense of objective reduction due to decoherent interaction of quantum objects with random influences in the classical environment. However, the probabilistic knowledge based on the mathematical quantum model can be said to ‘collapse’ into discrete non-probabilistic knowledge when the object is observed or measured, as discussed in relation to the Schrödinger’s cat paradox. The closest thing to a ‘collapse’ is the updating from probabilistic to definite knowledge based on sensory observation of the consensually-agreed upon *real* world of individual observers. But then how does Nature as a whole, the unified field of *Being*, change from possibilities to physical actualities apart from individual observers?

In the Sankhya model the infinitely self-interacting unified field of universal Being manifests into finite actualities of individual observers and individual objects. This process occurs naturally in a manner similar to spontaneous sequential symmetry-breaking, as levels of nature are expressed in increasing limitations. This is in contrast to the decoherence model. In this Vedic model the gross physical environment of particle interactions manifest from the subtler level of nature; and then the particles can combine to structure microscopic and macroscopic objects in the gross physical level of nature. It is on the subtle level where the subject-object duality becomes expressed, prior to manifestation of the gross level. The self-referral, self-interacting dynamics of manifesting subject-object duality is in the structure of the *Veda* itself.

When an observation is made by a *real* conscious observer of the *real* and already existing subtle and gross natural world, the



observer gains specific knowledge of it. This reflects the self-correcting scientific method of empirical validation fundamental to science. Validation through empirical experience updates and advances theoretical knowledge of it. In this model the notion of collapse is best applied in terms of a change in knowledge state of the observer from mathematical possibilities to specific knowledge upon observation.

According to the Vedic model, *reality* changes in different developmental states (Maharishi, 1967; Boyer, 2010). In the ordinary waking state typically associated with physicalist realism, the physical seems to be the most *real*. In contrast, in the highest state such less developed experiences are said to be illusory in the sense that they reflect finite partial values rather than the infinite eternal unity. Finite partial values are associated with the concept of ‘*Maya*,’ which refers to *measurable existence*. These gross and subtle levels of existence are within finite time and

distance, and are said to be conditional *realities*, in comparison to the immeasurable, non-changing unity.

Eventually ultimate knowledge naturally arises that the phenomenal observer, process of observing, and observed are nothing other than the *real* infinite eternal unified field of universal Being, associated with the developmental perspective of Vedanta (Boyer, 2012, 2008). Each of us as individual conscious beings are said to exist as waves in the unbounded cosmic ocean of universal Being. In that view of the totality of nature in the 3-in-1 Vedic model, the answer to ‘Is there a collapse of the quantum wave function?’ would then be, ‘not *really*.’

References

- Bohm D. Wholeness and the implicate order, London. Routledge & Kegan Paul, 1980.
- Bohm D, Hiley BJ. The undivided universe, London. Routledge, 1993.
- Boyer RW. Linking mind and matter: a new perspective for a scientific model that unifies nonlocal mind and local matter, Malibu, CA. Institute for Advanced Research, 2012.
- Boyer RW. Think outside the bang: beyond quantum theory and hidden dimensions to a holistic account of consciousness, mind and matter, Malibu, CA. Institute for Advanced Research, 2010.
- Boyer RW. Bridge to unity; unified field-based science and spirituality, Malibu, CA. Institute for Advanced Research, 2008.
- Dickson MW. Quantum chance and non-locality, Cambridge. Cambridge University Press, 1998.
- Everett H. “Relative state” formulation of quantum mechanics. Review of Modern Physics 1957; 29: 454-462.
- Folger T. Quantum shmantum. Discover 2001, September.
- Goldstein S. Quantum theory without observers, Physics Today 1998, March, 42-46; April, 38-42.
- Goswami A. The self-aware universe: how consciousness creates the material world. New York. GE. Putnam’s Sons, 1993.
- Greene B. The fabric of the cosmos: space, time, and the texture of reality, New York. Alfred A. Knopf, 2004.
- Hagelin JS. Is consciousness the unified field? A field theorist’s perspective, Modern Science and Vedic Science 1987; 1: 1.
- Hagelin JS. Restructuring physics from its foundation in light of Maharishi’s Vedic Science. Modern Science and Vedic Science 1989; 3(1): 3-72.
- Herbert N. Quantum reality: beyond the new physics, New York. Anchor Books, 1985.
- Loewer B, Albert D. Interpreting the many worlds interpretation. Synthese 1988; 77: 195-213.
- Maharishi Mahesh Yogi. Maharishi Mahesh Yogi on the Bhagavad-Gita: a new translation and commentary, chapters 1-6, Baltimore MD. Penguin, 1967.
- Maharishi Mahesh Yogi. Science of Being and art of living, Washington, DC. Age of Enlightenment Press, 1963.
- Penrose R. The road to reality. a complete guide to the laws of the universe, New York. Alfred A. Knopf, 2005.
- Smolin L. Three roads to quantum gravity, New York. Basic Books, 2001.
- Stapp HP. The hard problem: a quantum approach. In Shear J., Ed. Explaining consciousness—the hard problem, Cambridge, MA. The MIT Press, 2000; pp. 197-215.
- Stapp HP. Mindful universe: quantum mechanics and the participating observer, Berlin Heidelberg New York. Springer-Verlag, 2007.
- Talbot M. The holographic universe, New York. HarperCollins Publishers, Inc., 1991.
- Tarlaci S. The Measurement problem in quantum mechanics: well, where’s the problem? NeuroQuantology 2012; 10: 216-229.
- Varela FJ., Thompson, E., Rosch, E. The embodied mind: cognitive science and human experience, Cambridge, MA. The MIT Press, 1993.
- von Neumann J. Mathematische Grundlagen der Quantenmechanik, Berlin. Springer Verlag. Trans. Beyer RT, 1955. Mathematical foundations of quantum mechanics, Princeton. Princeton University Press, 1932.
- Zeh HD. On the interpretation of measurement in quantum theory. Foundations of Physics 1970; 1(1): 69-76

