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Quantum Interactive Dualism: The Libet and Einstein-Podolsky-Rosen Causal Anomalies

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Abstract: Replacing faulty nineteenth century physics by its orthodox quantum successor converts the earlier materialist conception of nature to a structure that does not enforce the principle of the causal closure of the physical. The quantum laws possess causal gaps, and these gaps are filled in actual scientific practice by inputs from our streams of consciousness. The form of the quantum laws permits and suggests the existence of an underlying reality that is built not on substances, but on psychophysical events, and on objective tendencies for these events to occur. These events constitute intrinsic mind-brain connections. They are fundamental links between brain processes described in physical terms and events in our streams of consciousness. This quantum ontology confers upon our conscious intentions the causal efficacy assigned to them in actual scientific practice, and creates a substance-free interactive dualism. This putative quantum ontology has previously been shown to have impressive explanatory power in both psychology and neuroscience. Here it is used to reconcile the existence of physically efficacious conscious free will with causal anomalies of both the Libet and Einstein-Rosen-Podolsky types.

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1. Introduction

We all feel that certain of our conscious thoughts can *cause* our voluntary bodily actions to occur. Our lives, our institutions, and our moral codes are largely based on that intuition. The whole notion of "cause" probably originates in that deep-seated feeling.

The strongest argument against this basic intuition---that our thoughts *cause* our voluntary bodily actions---stems from an experiment performed by Benjamin Libet (1985, 2003). In this experiment a subject is instructed to perform, voluntarily, during a certain time interval, a simple physical action, such as raising a finger. Libet found that a measurable precursor of the physical action, known as the "readiness potential", occurs in the brain about one-third of a second prior to the occurrence of the psychologically described act of willing that action to occur.

This empirical result appears to show, on the face of it, that the conscious act of *willing* must be a *consequence* of this associated brain activity, not the *cause* of it, for, according to the normal idea of cause, nothing can cause a prior happening to occur.

This example is just one instance of a general feature of mind-brain phenomena, namely the fact that conscious experiences always seem to occur after a lot of preparatory work has already been done by the brain. This feature accords with the classical-physics precept of the causal closure of the physical, and it leads plausibly to the conclusion that the felt causal efficacy of our conscious thoughts is an illusion.

One of the most intensely studied aspects of quantum mechanics is the occurrence of correlations in which a "voluntary" choice made at one time appears to affect events that occurred earlier than this choice, or simultaneously with it yet faraway. These correlations were the basis of a famous paper published in 1935 by Albert Einstein and two younger colleagues, Boris Podolsky and Nathan Rosen. The existence of certain puzzles associated with these correlations is called the EPR paradox. These correlations are correctly predicted by quantum mechanics, but they cannot be comprehended within the conception of the physical world postulated by classical mechanics.

In both the Libet and EPR cases the existence of these apparent causal anomalies suggests that what seems to us to be "voluntary" free choices are actually mechanically determined by the physically described aspects of nature, in keeping with the precepts of classical physics. However, the founders of quantum theory were driven, in their search for a rationally coherent understanding of various twentieth century data, to a theory that consistently treats our voluntary choices as "free choices". They are free in the sense that they are not determined by any currently known laws, even though they have, according to the laws of quantum mechanics, specified physical consequences, This article describes how orthodox quantum mechanics reconciles this idea of physically effective voluntary "free choices" with the Libet and EPR data

2. From Classical Mechanics to Orthodox Quantum Mechanics

During the seventeenth century Isaac Newton created the foundations for what developed during the eighteenth and nineteenth centuries into what is now called classical physics, or classical mechanics. Classical mechanics conceives the physical world to be composed of classically conceived particles and classically conceived fields. Classically conceived particles are like miniature planets that move though space under the influence of fields of force generated by the other particles. This entire physical structure develops in time in a way fixed by mechanical laws that *entail the causal closure of the physical*: the whole physically described structure is determined for all time by these mechanical laws---which refer only to these physically described elements themselves---together with initial conditions on these physically described parts.

Around the beginning of the twentieth century it was discovered that this classical-mechanical conception of the physical world was incompatible with the behaviors of large (visible) systems whose activities depended sensitively upon the behaviors of their atomic constituents. The classical conception of physical reality was therefore abandoned by physicists, at the fundamental level, and was replaced by a vastly different conceptual arrangement.

The logical basis of this conceptual change is a curious mathematical change. To pass from a classically conceived physical system to its quantum generalization the *numbers* that described the classically conceived physical properties are replaced by *mathematical actions*, called *operators*.

A principal difference between numbers and mathematical actions/operators is that the order in which one multiplies numbers does not matter---2 times 3 is equal to 3 times 2---but the order in which one applies actions does matter: for two actions A and B, the action of A followed by the action of B, which, for historical reasons, physicists represent as BA is not equal, in general, to AB.

The paradigmatic example is this.

An important number in classical physics is the number x that represents how far some object has been displaced, in some direction, from an initial point x=0. An equally important number is the number p that represents the momentum $p = mv$ of the object, where m is the mass of the object, and v is its velocity in the direction associated with x. In classical physics x and p are *numbers*, and hence $xp - px = 0$, but in the quantum counterpart of the classical system $xp\text{-}px= i\hbar$, where $\hbar$ is a number discovered and measured by Max Planck in 1900, and i is a number that multiplied by itself gives minus one.

This difference between classical mechanics and quantum mechanics might seem to be a mere mathematical technicality, having no deep conceptual import. Indeed, the smallness on the scale of human activities of the effective difference between numbers and the corresponding mathematical actions, might naturally lead one to expect that the *conceptual* changes needed to cope with this mathematical change would be unimportant at the level of human beings and their actions. But this is apparently not the case. The founders of quantum theory, in order to secure a rationally coherent and consistent way of dealing, in a scientifically satisfactory manner, with the technical problems introduced by the replacement of numbers by actions were forced to formulate their theory in terms of *actions*, and in particular the actions of human investigators. Specifically, their theory is formulated in terms of predictions about the observable responses to actions that are chosen *by human agents,* with the intent to probe certain properties of systems described in the mathematical language of quantum mechanics. But this means that the basic physical theory deals *no longer with intrinsic properties of physically described systems*, but, fundamentally, with the interplay between observed and observing systems. And these observing systems are, paradigmatically, conscious human participants. Here the word "conscious" highlights the fact that the theory involves, basically, not solely the physical language of the quantum mathematics, but, equally importantly, also the concepts and language that we human beings use to communicate to our colleagues "what we have done and we have learned". Moreover, the theory involves, in a fundamental way, also the so-called "free choices on the part of the experimenter", which are experienced by experimenters as conscious choices.

Any physical theory, to be relevant to our lives, must link certain mathematical features of the theory to the streams of consciousness of human beings. Quantum theory is built squarely upon the recognition of this fact

To see how this works, consider the mathematical action x discussed above. As already mentioned, this mathematical action x replaces the number x that in classical mechanics specifies where (along a straight line) the (center of an) object is located. The postulated correspondence between the quantum mathematics and experienced perceptions ties the *mathematical action* x *to the empirical probing action that would yield, as its perceived outcome, the number x that would specify the location of the object being probed, insofar as that object has a well defined location.* Similarly, the mathematical action p is tied to a physical probing action that would yield as its perceived outcome the number p that specifies the momentum of the observed object, insofar as that momentum is well defined.

Not every possible mathematical action has a perceptual counterpart. But the basic interpretive assumption in orthodox contemporary physics is that every possible probing action with a perceivable outcome has, in the quantum mathematics, an action counterpart: an associated operator. *Thus an intrinsic mind-matter connection is built directly into the fabric of our basic physical theory*.

This profound difference between contemporary physical theory and the classical physical theories of the eighteenth and nineteenth centuries would appear, prima facie, to be relevant to issues pertaining to the relationship between mind and matter. The earlier theories are approximations to the newer theory, and these approximations systematically exorcize, in a rationally coherent but physically inaccurate way, dynamical connections between mind and matter that the newer theory incorporates.

The connection between mind and matter occurring in the original *pragmatic* formulation of quantum mechanics, which is known as the Copenhagen interpretation, was converted to a connection between mind and brain by an elaboration upon the Copenhagen interpretation developed by the renowned logician and mathematician John von Neumann. This developed form was named "the orthodox interpretation" by von Neumann's close colleague Eugene Wigner, and it is the starting point of most, if not all, investigations into the nature of the reality that lies behind the pragmatically successful rules of quantum mechanics.

In spite of this seemingly relevant twentieth century development in physics, contemporary neuroscience and philosophy of mind continue to base their quests to understand consciousness on an essentially nineteenth century conceptualization of the human brain, ignoring the facts that the older conception of reality has been known to be false for almost a century, and that, in stark contrast to the nineteenth century conceptualization, contemporary orthodox physics has specified dynamical connections between brains and minds built intrinsically into it.

Planck's constant is a very tiny number on the scale of human activities. Consequently, the replacement of a classical system by its quantum counterpart turns out to be unimportant for predictions pertaining to the observable properties of physical systems whose behaviors are insensitive to the behaviors of their atomic-sized constituents. But the behaviors of brains are understood in terms the behaviors of the ions flowing into and out of neurons. So it is not clear, a priori, that the behavior of a conscious brain will, in every case, be essentially non-dependent upon how its atomic-sized constituents behave. Indeed, quantum calculations (Stapp, 2004a) pertaining to the release of neurotransmitter molecules into the synaptic clefts separating communicating neurons show that quantum effects are important in principle. According to the principles of contemporary physics the behavior of a living brain must *in principle* be treated as a quantum mechanical system, with classical concepts applied only when justified by special circumstances.

No computations have ever shown that a conscious human brain can be validly treated in the classical approximation. On the other hand, the three-century-old effort to understand the connection between mind and brain within the conceptual framework of materialist classical physics has led to profound conceptual difficulties. These difficulties have provided fertile ground for philosophical disputes that have enlivened the fields of philosophy of mind and neurophilosophy without producing much consensus. But one point of near unanimity is the conclusion that materialism is surely the adequate and appropriate theoretical foundation: for the scientific study of consciousness: that the injection by twentieth century physics of the effects of conscious choices made by observer-participants into the basic dynamics of physical systems can safely be ignored. Still, however, a rationally coherent conceptualization that has *specified* mind-brain dynamical connections---that arise from the basic precepts of empirically valid physics---could conceivably provide a more adequate foundation for the scientific study of the behavior of actually existing mind-brain systems than a nineteenth century approximation that is inadequate in principle for systems whose behaviors depend significantly upon the dynamics of their atomic constituents, and that systematically exorcises the quantum-physics-mandated dynamical effects of conscious choices made by conscious agents.

Over the past few years, I have been engaged in an effort to introduce into the scientific studies of consciousness certain basic results pertaining to the dynamics of the mind-brain system that are entailed by orthodox contemporary physics. Numerous application have been made in the domains of psychology, psychiatry, and neuroscience. (Stapp, 2004a, 2005, 2006a-d); Schwartz, Stapp, and Beauregard, 2005) I shall give here first a brief summary of some of the key elements of this quantum approach, and then use the theory to give a unified treatment of the Libet and the Einstein-Rosen-Podolsky data.

Classical physics is nominally about the *internal properties* of physical systems, but is known to be fundamentally false. It has been replaced by quantum physics, which is about the *interplay* between *observed systems, described in terms of mathematical quantities attached to space-time points (~* res extensa*), and observing systems, described in terms of elements of streams of consciousness (~* res cogitans).

Although the various *effects* of a probing action made by a probing system upon a probed system are specified by quantum theory, the *cause* of the probing action is not specified by the theory. There is, therefore, a causal gap! The quantum-theoretic laws determine neither when a probing action will occur, nor which aspects of the observed system will be probed. Niels Bohr emphasizes this key feature of quantum mechanics when he says:

> "The freedom of experimentation, presupposed in classical physics, is of course retained and corresponds to the free choice of experimental arrangement for which the mathematical structure of the quantum mechanical formalism offers the appropriate latitude." (Bohr, 1958, p.73)

> "To my mind there is no other alternative than to admit in this field of experience, we are dealing with individual phenomena and that our possibilities of handling the measuring instruments allow us only to make a choice between the different complementary types of phenomena that we want to study. (Bohr, 1958, p. 51)

In practical applications, in both classical and quantum mechanics, physicists treat the human experimenter as an agent who sets up experiments on the basis of his reasons. In neither classical nor quantum theory does anyone actually use the dynamical equations to determine what a real experimenter will actually do. The brain is too complex and too inaccessible to non-disturbing observations at the needed level of accuracy to permit this. In classical physics there is the *presumption* that the physical laws determine *in principle* what an experimenter will do. But this presumption goes far beyond what has been scientifically tested and confirmed. In the more accurate contemporary orthodox quantum theory the conclusion is just the opposite: *in principle the known laws definitely do not determine how the experimenter will act, or even place statistical conditions on these choices*. To fill this lacuna the founders of quantum mechanics brought into the theory certain inputs from conscious human beings, namely their choices of their own actions. This introduction of physically efficacious conscious choices into the physical theory in a fundamental way was the most radical of the breaks with precedent introduced by the founders of quantum theory, and is the one most vigorously opposed by physicists seeking a closer-to-tradition alternative to the Copenhagen and orthodox (von Neumann) approaches. However, none of the proposed alternatives appears to be satisfactory, as yet, even to its supporters. (See Appendix A of Schwartz, et al., and the references cited there, most particularly Stapp 2002, and also Stapp 2006a-d)

Specifically, quantum theory brings into the causal description, in addition to the (sometimes-violated) deterministic continuous evolution in accordance with the quantum generalization of the deterministic classical process of evolution, also *choices of two kinds,* both of which are implemented, or represented, by abrupt "quantum jumps" in the continuous deterministic evolution. One of the two kinds of choices determines the familiar collapse of the wave function (or reduction of the wave packet). It is called by Dirac a "choice on the part of nature", and it is a choice---from among the several alternative possible outcomes of a probing action performed upon an observed/probed system---of *one particular outcome*. These choices "on the part of nature" are "random": they are asserted by the theory to conform to certain statistical conditions. These "choices on the part of nature" are precisely where the randomness enters (irreducibly) into contemporary physics.

But, according to the orthodox precepts, this statistically governed "choice on the part of nature" *must be preceded* by another choice: a choice of which (probing) experiment is to be performed, and when it will be performed. No known laws constrain *this choice of the probing action*, and it is consistently treated in orthodox quantum theory as "a free choice on the part of the experimenter" This "choice on the part of the experimenter" fixes the form of the physically/mathematically described probing action. The representation *within the quantum mathematics* of this probing action is called by von Neumann "Process 1".

The *logical* need for this choice*, which is not specified by any known law,* persists, even when the quantum-mathematically described part of the universe---which in the original Copenhagen interpretation does *not* include either the body or the brain of the observer, or even his or her measuring devices---is expanded (by von Neumann) to include the entire physical universe, *including* the bodies and brains of the observers. The essential point is that the inclusion of the body and brain of the human agent/participant into the quantum-mechanically described universe *still leaves undetermined* the choices made by that human person

This logically needed choice is relegated, in von Neumann's words, to the experimenter's "abstract ego". But no matter what words are used, the fact remains that the inclusion of the body and brain of the observer into the physically described quantum world leaves undetermined the *logically needed choice* of which physical Process1 probing action actually occurs. No known law, statistical or otherwise, specifies which probing action, Process 1 action, actually occurs.

The choosing process, whatever it is, that specifies this choice of the actually occurring Process 1 is called Process 4. Process 2, so-named by von Neumann, is the continuous deterministic evolution via the Schroedinger equation, whereas Process 3 is the choice on the part of nature of which outcome/feedback from the probing action actually occurs, Process 2 reigns only during the intervals *between* the various abrupt Process 1 and Process 3 quantum jumps.

This need for the occurrence of physically efficacious Process 4 choices that are not determined by any known law, statistical or otherwise, constitutes a prima facie breakdown, within orthodox quantum mechanics, of the doctrine of the causal closure of the physical. Quantum theory, as it is taught to physicists in their university courses, is presented as a set of rules that allow scientists to form expectations about the feedbacks they will receive by performing any *one* of many possible probing actions, between which they are free to choose. This practical format is the basis of the conceptual structure of quantum theory.

To prepare the way for the analysis to follow I need to spell out in slightly more detail the structure compactly summarized above.

The conversion of the classically conceived universe to its quantum generalization---obtained by replacing numbers by actions---is called *quantization*. It converts the classical deterministic equation of motion into its quantum counterpart, called “Process 2” by Von Neumann. Like its classical counterpart, this quantum law of evolution is deterministic: left alone, it would determine the quantum state of the universe for all times from its primordial form. The relativistic (quantum field theoretic) form of this law is moreover *local*: the changes in the quantum state associated with any region are determined by the properties associated with very nearby regions, and no influence propagates faster than the speed of light.

This Process 2 evolution, by itself, is dynamically insufficient. Given some initial conditions it produces at a later time not the mathematical counterpart of *one single perceptual probing action*, but rather the counterparts of a *continuous smear* of alternative possible probing actions. Orthodox quantum theory resolves this difficulty by supplementing the Process 2 evolution by certain abrupt changes, which von Neumann calls “Process 1 interventions”. Each such mathematical intervention is tied by the quantum laws to a particular perceivable probing action performed upon the observed system by an observing system external to it.

Neither the property of the observed system that is probed by this intervention, nor the time when this probing action occurs, is fixed by the mechanical Process 2. These two features are considered to be fixed by the observing system. This assignment of responsibility, or of causal origin, accords with the fact that in actual scientific practice it is the human experimenter that selects, by conscious choice, which particular probing action will be performed upon the system he or she is observing, and when that probing action will be performed. Of course, an agent’s conscious choices are not independent of what is going on in his brain, but *orthodox contemporary physics does not determine* how the psychic and physical components of reality combine to *cause* the Process 1 events to be what they turn out to be.

The *effect* of the Process 1 intervention upon the observed system *is* specified by the quantum laws. This intervention selects from the smear of possible probing actions some particular one. The effect of this singled-out probing action upon the mathematically described state of the observed system is this: it separates this state into a set of disjoint (i.e., non-overlapping) components in a way such that: (1), the statistical weights assigned by the theory to these individual components adds to unity; and (2), each component corresponds to a *phenomenologically distinct* outcome of that probing action.

After this Process 1 separation has been made, nature picks out, and saves, *one* of the possible psychophysical outcomes of the chosen probing action, and eradicates the rest. *Nature’s* selection of outcomes---called Process 3 in my terminology---is asserted by the theory to respect the statistical weights assigned to the alternative possible outcomes. The quantum mathematical structure becomes tied in this way to phenomenology, and the theory generates practical rules that allow statistical predictions pertaining to experiences to be deduced from the postulated mathematical structure.

This injection of human volitional choices into the physical dynamics *at a basic level* is completely contrary to the precepts of classical physics. But this change accommodates the fact that we human beings do in fact inject our conscious intentions into the physically described world whenever we act intentionally. Accepting quantum mechanics opens the door to the possibility of a more detailed, *and more useful,* putative understanding of this effect of conscious intent than classical mechanics can provide.

3. The Libet Causal Anomalies

In the Libet experiment the initial intentional act is to choose willfully to perform, at some future time within, say within the next minute, the act of raising a finger. We often make such resolves to act in some specified way at some future time, and these commitments are often met with great precision. However, in the Libet case the resolve is rather imprecise as regards the exact time of the specified action. It is doubtful that any person, informed even by a multitude of probing devices about the state of the subject's brain at the beginning of the specified interval, could predict with good accuracy just when the choice to move the finger will occur. And even if every neurophysiological-level feature of the brain were given at the outset, it is still questionable whether, even in a world that obeyed the deterministic laws of classical physics, this macroscopic data would fix the time at which the conscious choice occurs. There is just too much latitude for initially small-scale variations to develop over the course of time into significant macroscopic effects. Even within deterministic classical physics the best one could do with actual macroscopic data would be to make a statistical model based on that data and the known general properties of the brain.

In the case of the dynamics of a warm wet living human brain, interacting with its environment, almost all quantum interference effects *connecting appreciably different locations* will (almost certainly) be washed out, and the quantum model will become similar to a classical *statistical* model that features a collection of parallel classically conceived worlds, each with some statistical weight. However, in the classical case one can imagine that exactly one of the statistically weighted alternative classically conceived possibilities is the "real" one, and that the statistical smearing represents a mere lack of knowledge as to which of the weighted possibilities represents the "actual real world".

This "lack of knowledge" interpretation cannot be carried over to quantum theory. However, to a good approximation, the various weighted classically conceived worlds of classical statistical theory can be understood to represent *simultaneously existing potentialities*, some subset of which will eventually be selected by some Process 1 probing event. This Process 1 action will be followed by a Process 3 choice (on the part of nature) that specifies which of the alternative possible outcomes of the chosen probing action actually occurs. *All potentialities that do not lead to the outcome that* *actually occurs are eradicated by these collapse or reduction events, leaving only those that lead to the psychophysical event that actually does occur.*

In the Libet experiment, the mind-brain "set" fixed by the initial conscious intention to raise the finger within the next minute should cause the quantum mechanically described brain to generate classically describable potentialities corresponding to the various alternative times at which the specified conscious act could occur. Thus the following scenario is compatible with quantum mechanics, and is suggested by it.

The initial intent (to raise the finger within the next minute) will lead to the production of a collection of parallel potentialities, each corresponding to a possible time at which the readiness potential can start its build up. Shortly after some of the classically described potentialities have developed to the point of specifying a certain possible perceivable probing action the question will pop into the stream of consciousness: "Shall I perform this action?" If the answer is 'No', as it is likely to be right at the beginning, then the potentialities *leading up to the performance of that action at that time* will be eradicated. A short time later a similar Process 1 question will be posed. The outcome is again likely to be 'No', and the batch of potentialities leading to the 'Yes' option will again be erased. Eventually, in accordance with the statistical rules, a 'Yes' outcome will be selected by nature, and the set of potentialities leading to the 'No' outcome will be wiped out. Only the (essentially classically described) potentialities *leading to* this 'Yes' outcome will remain.

The "Yes" event is a psychophysical event that is felt or experienced as the feeling or knowledge "I shall now raise my finger", and it is represented in the physically described world as the actualization, at that moment, of the neurological activity that constitutes the template for the action of raising the finger. (This template is a neural/brain activity that, if held in place for a sufficiently long interval, will tend to cause the finger to rise.) All brain activities---*which have the ontological character of potentialities*---that are incompatible with this intent are *eliminated by this event* from the quantum mechanical state of the brain. Hence they are eliminated from the statistical mixture of classically described states that approximately represents this quantum state.

Now suppose there is in place some measuring device that can, in the approximately correct classical description of what is (possibly) going on, detect the time at which the readiness potential starts its build up. This time of the inception of the build up is long (one-third of a second) before the psychophysical event that will, *only later,* actualize this particular classically described world. Now suppose, furthermore, that the classically described measuring device activates a classically described timer that records the time of the beginning of the build up of the readiness potential. This classically described *record* of the time of the start of the build up of the readiness potential will continue to exist along side the increasing readiness potential. When some person, at some later time, after the occurrence of the psychophysical event that determines which of the classically described worlds survives---and hence that determines also the time at which the build-up of the readiness potential began---reads the timer he will find out that the start of the build up of the readiness potential occurred *before the occurrence of the psychophysical event that selected the classical world that specifies the time when that build up began.*

The key point here is that the *record* of the time of the start of the build up of the readiness potential is *a causal off shoot* of this build up, and this record will be actualized along with the actualization of the potentiality *represented (to a good approximation) by* the classically described process that the actualization event selects. Thus the recorded time of the beginning of the build up of the readiness potential will be earlier than the time of the event that actually determined (according to this quantum ontology) the time of the beginning of this build up: the recorded time of the beginning of the build up will be fixed by an event that occurs only later.

Such seeming causal anomalies have been a prime point of attack on orthodox quantum theory, and they continue to fascinate physicists even today, under the names “quantum nonlocality”, or “Bell’s theorem”, or “EPR paradox.” Although this quantum ontological way of understanding the quantum correlation tends to upset people accustomed to thinking about the world in classical mechanical terms, no logical inconsistency or conflict with empirical data has ever been established. One can be quite confident in accepting that all of the known empirical evidence is compatible with this non-classical but logically consistent “quantum ontological” conception of how the world works.

On the other hand, one can certainly adhere, alternatively, to the *pragmatic* point of view, which holds that, even though this quantum ontology accords with all of the empirically verified relationships between human experiences, and seems to provide a coherent putative “understanding” of what is going on, this success by no means implies that this understanding is veridical. For one can express the empirical predictions in compact ways that avoid any commitment concerning what is “really happening”. Thus many---and probably most---quantum physicists hold that, as scientists, the pragmatic option is all they need to commit to. On the other hand, for those who seek something more than merely “a set of rules that work” the quantum ontological model is a viable (i.e., not yet disproven) and logically coherent conception of the way that Nature actually works. The same cannot be said of local deterministic materialism.

Human agents play a very special role in this quantum ontology. This feature is a hold-over from the pragmatic stance of the original Copenhagen formulation of the theory, which was concerned principally with establishing a rationally coherent basis for practical applications. However, von Neumann’s analysis shows that there is no empirical evidence that *every* occurring collapse event is associated with an event in a human stream of consciousness. It is certainly more plausible, from a scientific perspective, to assume that there are similar events associated with other biological organisms, and there is no empirical evidence that confutes that position. Indeed, von Neumann’s analysis reveals, more generally, that collapse events that act *macroscopically* on physical systems that are interacting strongly with their environments would be virtually impossible to detect. There is presently no evidence that rules out the possibility that enormous numbers of macroscopic collapse events are occurring all the time in large systems that are strongly connected to their environments. Hence the special role originally assigned to human beings is no part of the general quantum ontological model being described here.

The main cause of reservations about the actual truth of this quantum ontology is that it entails faster-than-light transfer of information. These faster-than-light issues are essentially those that arise in the much-discussed EPR paradox.

4. The Einstein-Podolsky-Rosen Causal Anomalies

Albert Einstein, Boris Podolsky and Nathan Rosen, published in 1935 what is perhaps the most discussed scientific paper of the twentieth century. Entitled "*Can quantum mechanical description of physical reality be considered complete?*" the paper argues that Copenhagen quantum theory does not give a complete description of physical reality. The argument depends on a specific way of identifying what is meant by "physical reality". This identification depends on an assumption about the absence of influences that act backward in time or faster than the speed of light. Niels Bohr (1935) wrote a rebuttal that essentially admitted that the strong notion of no-faster-than-light influence used in classical-physics does indeed fail in quantum theory, but claimed that an adequate replacement holds within the epistemological framework of quantum mechanics.

The Einstein-Podolsky-Rosen argument is based on an examination of the predictions of quantum theory pertaining to certain correlations between *macroscopic* observable events that occur at essentially the same time in laboratories that lie far apart

A simple classical example of a correlation between events occurring at essentially the same time in far-apart laboratories is this. Suppose one has a pair of balls, one red, the other green. Suppose one loads them into two rifles, and fires them in opposite directions into two far-apart laboratories, in which the balls will be caught and examined at essentially the same time. The colors found in the two regions will obviously be correlated: if red is found in one lab then green will be found in the other, and vice versa. There is nothing strange or peculiar about a correlation of this kind.

The simplest quantum example is similar, and is again not in itself a problem. We can set up a *certain experimental arrangement of the macroscopic preparing and measuring devices* that will produce a situation analogous to the one with the two colored balls. Quantum mechanics predicts, and empirical evidence confirms, that, under these *macroscopically specified* experimental conditions, if a red light flashes on the detector in one laboratory, then a green light will flash at essentially the same time on the detector in the other laboratory, and vice versa.

Einstein and his colleagues (henceforth EPR) considered a slightly more complex situation in which there are two alternative possible settings of the measuring device in the first lab and two alternative possible settings of the device in the second lab. If the *first* setting is chosen in *both* labs then, as before, green in either lab entails red in the other, and vice versa. Moreover, if the *second* setting is chosen in *both* labs then, as before, green in either lab entails red in the other, and vice versa

A basic feature of quantum theory is this: the theory is mathematically incompatible with the idea that there exists *both* a property P1 that fixes which outcome will occur if the measurement in, say, the second lab specified by the *first* possible setting of the device in that (second) lab is performed, *and also, simultaneously,* a property P2 that fixes which outcome will occur if the measurement in the second lab specified by the *second* possible setting of the device in that (second) lab is performed. Quantum theory regards two such properties, P1 and P2, as *complementary* properties that cannot both exist simultaneously.

EPR devised an argument that seemed to show that these two properties P1 and P2 do exist simultaneously. Their argument produced consternation in Copenhagen. Bohr's close colleague, Leon Rosenfeld (1967) described the situation as follows:

> This onslaught came down upon us like a bolt from the blue. Its effect on Bohr was remarkable. We were then in the midst of groping attempts at exploring … [another problem] …. A new worry could not come at a less propitious time. Yet as soon as Bohr had heard my report of Einstein's argument, everything else was abandoned: we had to clear up such a misunderstanding at once. We should reply by taking up the same example and showing the right way to speak about it. Bohr immediately started dictating to me the outline of such a reply. Very soon, however, he became hesitant: "No, this will not do, we must try all over again … we must make it quite clear…" So it went on for a while with growing wonder at the unexpected subtlety of the argument. … Eventually he broke off with the familiar remark that he "must sleep on it." The next morning he at once took up the dictation again, … the real work now began in earnest: day after day, week after week, the whole argument was patiently scrutinized … .

What is the argument that set off this huge commotion, which reverberates even to this day?

Einstein and his colleagues introduced the following "criterion of physical reality":

> If, without in any way disturbing a system, we can predict with certainty (i.e., with probability equal to unity) a physical property of a system then there exists an element of physical reality corresponding to that property.

This criterion seems completely reasonable, and completely in line with the Copenhagen philosophy, which is built upon the idea of predictions of properties of systems as revealed by the observed outcomes of experiments performed upon those systems.

In the experimental situation just mentioned the setting of each device can be chosen and fixed *just before* the outcome at that device appears. The distance between the two labs can then be made so large that there is no time (according to the claim of the theory of relativity that *nothing* can travel faster than the speed of light) for *a choice of setting* in either lab to have any effect at all on *the faraway outcome*, red or green.

However, the experimenter in the first lab *can predict with certainty* the *property P1 that is measured by using the first setting in the (faraway) second lab.* He can do this simply by choosing the *first setting in his own (first) lab* and observing the outcome, red or green, and then inferring that P1 must be, respectively, green or red. The assumed---by EPR---impossibility of any faster-than-light or backward-in-time influence entails that this *action and act of observation in the first lab* cannot disturb in any way this property P1 measurable in the second lab. Thus, according to the EPR criterion, there is an element of physical reality P1 corresponding to the property that is measured in the second lab when one uses there the *first* setting.

By choosing the *second* setting in the first lab one finds that a property P2 corresponding to the *second setting* in the second lab is, likewise, an element of physical reality. But---for inescapable mathematical reasons---quantum theory cannot accommodate the simultaneous existence of these two elements, P1 and P2, of physical reality. Hence, as a description of physical reality, quantum theory must, according to EPR, be incomplete

EPR finish off their argument with the following crucial remark:

> One could object to this conclusion on the grounds that our criterion or reality is not sufficiently restrictive. Indeed, one would not arrive at our conclusion if one insisted that two or more physical quantities can be regarded as simultaneous elements of reality only when they can be simultaneously measured or predicted. On this point of view, since either one or the other, but not both simultaneously of the quantities P and Q can be predicted they are not simultaneously real. This makes the reality of P and Q depend upon the process of measurement carried out on the first system, which does not disturb the second system in any way. No reasonable definition of reality could be expected to permit this.
>
> [EPR's P and Q are essentially equivalent to our P1 and P2]

Bohr accepts that the orthodox principles of quantum theory demand that P and Q cannot, within that theory, both be assigned well defined values. How does he reconcile this fact with the EPR argument that both are elements or physical reality?

The essence of Bohr's reply (Bohr, 1935) is the following passage:

> From our point of view we now see that the wording of the above-mentioned criterion of physical reality proposed by Einstein, Podolsky, and Rosen contains an ambiguity as regards the meaning of the expression "without in any way disturbing the system." Of course there is in a case like that just considered no question of a mechanical disturbance of the system under investigation during the last critical stage of the measuring procedure. But even at this stage there is essentially the question of *an influence on the very conditions which describe the possible types of predictions regarding the future behaviour of the system.* (Bohr's italics.) Since these conditions constitute an inherent element of any phenomenon to which the term "physical reality" can be properly attached, we see that the argumentation of the above-named authors does not justify their conclusion that quantum-mechanical description is essentially incomplete.

If Bohr's argument strikes you as obscure, then you are not alone. Many philosophers and physicists have judged Bohr's reply to be insufficient, and have concluded that Einstein won the debate. Bohr himself says, in his contribution to the Einstein volume (Einstein, 1951, p. 234), "Reading these passages, I am deeply aware of the inefficiency of expression which must have made it very difficult to appreciate the trend of the argumentation….”

That is an accurate statement. Yet his later arguments do not seem to help.

One feature of Bohr’s answer does come across clearly: his reply rejects, *at some level*, Einstein’s idea of “without in any way disturbing the system”: Bohr rejects, at some level, Einstein’s assumption that the freely chosen measurement process performed in the nearby lab *does not disturb in any way* the system in the faraway lab, even though any such disturbance would have to act essentially instantaneously. That is, in order to rationally counter the Einstein argument Bohr found himself forced to reject Einstein’s principle that *all* causal actions act only forward in time, and no faster than the speed of light. If that principle fails, the EPR argument collapses.

Bohr’s point, in essence, is that once the experimenter in the first lab chooses to do one of the two possible measurements in his lab, for example the one specified by the first (resp. second) setting in his own lab, he loses the capacity to make any prediction about the outcome of a measurement in the other lab associated with the second (resp. first) setting in that faraway lab. Thus the experimenter’s choice of what to do here has changed *what he can know* about events in the faraway region. In an essentially epistemological theory in which the basic reality is “our knowledge”, a *reality* associated with the faraway lab can therefore *be said* to depend upon a one’s choice made here about what one will freely choose to do here. But then the EPR claim that no reality “there” can depend upon what one can freely choose to do “here” fails: the EPR argument goes down the drain.

Of course, an epistemologically based conception of reality goes against Einstein’s more traditional idea of reality. But this issue of the need of the basic physical theory to deal with non-epistemologically-based realities is the core issue in the Bohr-Einstein dispute. Hence, Einstein cannot simply assert, without in some way begging the central question, that “reality” must be defined non-epistemologically.

Bohr’s argumentation is basically philosophical, and about what we can know. It dodges the ontological issues usually associated with the phrase “physical reality”, which is normally *contrasted* to what we know, or can know. But the von Neumann-based quantum ontology described above explains the workings of this “action at a distance” in “ontological“ terms. This ontology incorporates Heisenberg’s idea of “potentia“ as an objective tendency for a physically describable event to occur in association with an increment in human knowledge. This ontology that is based not on *substances* but rather on psychophysical *events* and mathematically described “*objective tendencies*“ for such events to occur. These tendencies are non-substantive because they can change abruptly whenever a new psychophysical event occurs, perhaps faraway. It is, basically, the acceptance of such “*tendencies* as *objective realities”* that differentiates this Heisenberg-type quantum ontology from substance-based ontologies.

The quantum ontological explanation of the EPR-type correlations is similar to the explanation of the Libet back action. In the EPR case the actualization in one region of some particular probing action and its outcome actualizes also the particular causal chain that leads up to that outcome, *along with its causal off shoots*, and it eliminates the *potentialities* that would have produced the possible outcomes that were not actualized. But then a conscious choice of probing action made at one time and place can have ontological consequences in faraway regions. These faraway consequences are effects of *causal off shoots of possible processes that are actualized by events in the nearby region that depend on choices freely made in the nearby region.*

These words are more than verbal hand waving. They are descriptions in ordinary words of exactly what the von Neumann mathematical representation of the evolving state is doing. Insofar as one accepts the idea that the reality is represented by the mathematics, and that our words and concepts should conform to what the mathematics is saying, this quantum ontology follows. It is an accurate description of what the quantum mathematics is saying.

This ontology accords with the orthodox quantum principle that the properties P1 and P2, discussed above, do not exist simultaneously, and that the existence or nonexistence of such a property in one region can depend upon what a faraway experimenter does in a region that is space-like separated from the first. That is, this ontological conceptualization is in accord with the orthodox quantum principles, and it rejects, in agreement with Bohr's answer to EPR, the strong version of the principle of no faster-than-light effect *of any kind*. Bohr's rejection was, as already mentioned, essentially epistemological, and the quantum ontology translates this into a non-classical non-substantive ontological conceptualization that does bring into the dynamics effects of our "free" choices of how we will act.

One essential point needs to be emphasized. Von Neumann's formulation of quantum theory, which provides the mathematical foundation for this ontology, was first published in 1932, and it is non-relativistic. A state of the universe is given for each "instant of time". However, this formalism was generalized by Tomonaga (1946) and by Schwinger (1951) around the middle of the twentieth century to *relativistic quantum field theory*, with the quantum states now defined not on fixed-time surfaces but on space-like surfaces. (Every point of a fixed-time surface lies at the same time, whereas points on a space-like surface can lie at different times, but every point of a space-like surface is separated by a space-like interval from every other point on that surface.)

In this relativistic generalization, a Process 1 event, freely chosen and acting on a local (nearby) portion of a space-like surface, followed by some local (nearby) Process 3 outcome can "instantly" affect the part of the state associated with a distant (faraway) portion of that space-like surface. And this "faraway" effect can depend upon which Process 1 event was locally chosen. Thus Einstein's demand that such choices of probing actions can have *no faster-than-light influence of any kind* is violated, in accord with Bohr's denial of the validity of that condition. However, the relativistic formulation *does satisfy* the basic requirement of the theory of relativity that no "signal" can be transmitted faster than light. (A *signal* is a message such that the decipherable content received is influenced by the sender.) Thus in the robust practical sense of communicating what one knows (here) to distant receivers, there are no faster-than-light actions, even though the (Tomonaga-Schwinger) quantum ontology does explicitly exhibit faster-than-light transfers to faraway regions of information that is influenced by nearby free choices.. The reason that this explicit faster-than-light transfer of information cannot carry a message intended by the local experimenter is that the faraway effects of the nearby choice depends *jointly* upon the experimenter's choice of the local experiment and nature's choice of the local outcome in such a way that if the faraway receiver knows nothing about nature's local (nearby) choice then he cannot acquire from his observations any information about the experimenter's local (nearby) choice. This result is a direct consequence of the quantum rules.

The relativistic (Tomonaga-Schwinger) von Neumann ontology satisfies the demands of the theory of relativity, yet explicitly exhibits the sort of faster-than light effects alluded to in Bohr's answer to EPR. This rationally coherent conception of nature resolves the mysteries of the seeming causal anomalies by setting forth a new "quantum-theoretic" way of understanding nature; an understanding based not on substances but on psychophysical events and objective tendencies for such events to occur.

The fact that this particular orthodox ontology involves faster-than-light effects does not imply that *no* rationally coherent theory can agree with the quantum predictions unless it allows transfer of information about a free choice made in one region to a space-like separated region. But that strong result can be proved.

Certain theories entail the validity of certain statements of the form:

> If experiment 1 is performed and the outcome is A, then if, instead, experiment 2 had been performed the outcome would necessarily be B.

For example, according to classical physics, if we shoot a charged particle into a region with, say, uniform magnetic field H and it follows a semi circle of radius R then if we had chosen magnetic field 2H, with every other relevant thing unchanged, then the particle would have followed a semi-circle of radius R/2.

To establish the unavoidable need in any adequate theory of nature for some sort of faster-than-light transfer we may consider an experiment of the kind first investigated by Julian Hardy. As in the EPR case, there are two space-time regions situated so that nothing can get from either region to the other one without traveling either faster than light or backward in time. In each region either one or the other of two alternative possible probing actions can be chosen and performed. And, for each performed experiment, one or the other of two alternative possible outcomes of that experiment will appear in the region in which that measurement is performed.

Let one of the two regions be called R and the other be called L, and let the space-time region R lie *later* than the space-time region L (in some specified coordinate frame.) The first needed assumption is this:

> The choices of which of two possible experiments will be performed in regions R and L *can be treated* as independent free variables.

This does not mean that in the total scheme of things each of these two choices is undetermined until it actually occurs, but only that the choice of which experiment to perform can be fixed in so many alternative possible ways by systems so disconnected, prior to the probing action, from the system being probed, that the choice of which probing action is performed *can be treated* as a free variable in the context of the analysis of this experiment. This free choice assumption is endorsed by Bohr, and is used by EPR.

The second assumption is this:

> No matter which experiment is chosen and performed in the earlier region L, whatever outcome *appears and is recorded there* is independent of which probing action will be chosen and performed later in the faraway region R.

These two assumptions, along with the assumed validity of four simple predictions of quantum theory for a Hardy-type experiment allow one to *prove* some interesting properties of the following statement, which I have named SR, because it is a statement that refers to possible happenings in region R:

> SR:: If the first of the two alternative possible probing actions in region R gives the first of the two possible outcomes, then the second of the two alternative possible probing actions in region R, if it had been performed instead of the first one, would necessarily have given the first possible outcome of that second probing action.

This statement does not involve two co-existing incompatible properties: the two incompatible properties in R exist only under incompatible conditions in R

Statement SR is *logically entailed by the two assumptions described above and the validity of four predictions of quantum theory* to be true or false according to whether the experimenter in region L chooses to perform in L one or the other of the two alternative possible actions available to him or her. (Stapp, 2004b)

The conditions that logically determine whether this statement SR is true or false are conditions on outcomes appearing in region R under the alternative possible conditions that can be freely chosen in that region R. But this statement is required by the laws of quantum mechanics to be true or false according to which choice is freely made by the experimenter in region L, which is space-like separated from region R. This demand cannot be met by a theory that allows no information about the free choice made in L to get to the region R.

A rationally coherent understanding of natural phenomena that allows our choices of which experiments we perform to be treated as free variables is logically possible, but any such theory that strictly enforces the principle of no faster-than-light or backward in time transfer of information appears to be excluded by this argument, which thereby removes an important barrier to the acceptance of the quantum ontology described above.

5. Application to Libet

Numerous applications of this quantum ontology to the understanding of phenomena in psychology, psychiatry, and neuroscience related to the connection of mind to brain have been described in Schwartz (2005). The central idea is to begin to fill the lacuna in the causal structure associated with Process 4---the process of choosing *which* Process 1 will occur, and *when* it will occur---by distinguishing two kinds of Process 4 choices: passive choices and active choices. The passive choices are entailed by brain activity alone: for these passive choices the Process 1 action occurs when an associated threshold in brain activity is reached. The expression of this physically described threshold remains to be specified. (cf. Stapp, 1999) Once this initial psycho-physical event occurs, and the follow-up Process 3 outcome has produced a 'Yes' response, there can be a felt evaluation. The key assumption is that if this felt evaluation is sufficiently positive then there may be an *active* effort to attend to this idea, which, if sufficiently strong, will produce an almost immediate repeat of the original psychophysical event associated with Process 1. If the repetitions are sufficiently rapid then a well-known quantum effect, the quantum Zeno effect, will cause a long string of essential identical Process 1-Process 3 pairs to occur. This rapid sequence of events will, by virtue of the known quantum rules, tend to hold in place the associated template for action, and this will tend to cause the intended action to occur. Thus conscious intentions motivated by felt valuations become injected into the brain dynamics in a way that tends to cause consciously intended actions to occur. (See Stapp 2004a, Chapt. 12 for the mathematical details.)

This conception of what is going on is in close accord with William James's assertions (James, 1892)

> I have spoken as if our attention were wholly determined by neural conditions. I believe that the array of things we can attend to is so determined. No object can catch our attention except by the neural machinery. But the amount of the attention which an object receives after it has caught our attention is another question. It often takes effort to keep mind upon it. We feel that we can make more or less of the effort as we choose. If this feeling be not deceptive, if our effort be a spiritual force, and an indeterminate one, then of course it contributes coequally with the cerebral conditions to the result. Though it *introduce* no new idea, it will deepen and prolong the stay in consciousness of innumerable ideas which else would fade more quickly away. The delay thus gained might not be more than a second in duration---but that second may be critical; for in the rising and falling considerations in the mind, where two associated systems of them are nearly in equilibrium it is often a matter of but a second more or less of attention at the outset, whether one system shall gain force to occupy the field and develop itself and exclude the other, or be excluded itself by the other. When developed it may make us act, and that act may seal our doom. When we come to the chapter on the Will we shall see that the whole drama of the voluntary life hinges on the attention, slightly more or slightly less, which rival motor ideas may receive. ...
>
> Consent to the idea's undivided presence, this is efforts sole achievement

This understanding is in line also with James's assertion (James, 1911):

> your acquaintance with reality grows literally by buds or drops of perception. Intellectually and on reflection you can divide them into components, but as immediately given they come totally or not at all.

Turning to the Libet situation, we see that there is an important difference between it and the EPR situation. In the Libet case the initial action that initiates the agent's later actions, namely the agent's commitment to raise the finger sometime during the next minute, occurs *before* the development of the causal offshoot, and it generates the chain of events associated with both the creation of the causal offshoots (namely the creation of the *records* of the beginnings of the various parallel build-ups of the readiness potential) and also the subsequent conscious probing actions, one of which will eventually lead to the actualization of *one* of these records. This causal linkage breaks, in the Libet case, the control of the *active* conscious choice (to raise the finger now) upon the causal off shoot (the record). In the Libet case these *active* conscious choices act only to hold the template for action in place long enough to cause the finger to rise, or, by failing to so act, to effectively *veto* that physical action. Thus the *active* conscious choices do not influence the causal off shoots in the efficacious way that they do in the EPR case. They act only either to consent to the process of raising the finger, caused by the initial commitment to do so and nature's subsequent "Yes", or to veto this physical action by refusing to initiate the repetitions needed to produce the action. (See e.g, Schwartz et. al.) However, in the generation of correlations between two phenomena occurring different regions, the key role of an actualization of a potentiality having a causal off shoot is the same in both the Libet and EPR cases, as is the explanation of the capacity of a person's conscious choices, unconstrained by any yet-known laws, to influence his physical actions.

6. Conclusion

The quantum mechanical understanding of the mind-brain dynamical system explained and defended in Schwartz (2005), and further elaborated in Stapp (2005) and Stapp (2006), accommodates, and putatively explains, the ability of our conscious intentions to influence our physical behavior. This theory covers in a natural way also the Libet data. It reconciles Libet's empirical findings with the capacity of our conscious intentions to influence our actions, without these intentions being themselves determined by the physically described aspects of the theory. This separation is achieved by exploiting a causal gap in the mathematically expressed laws of quantum mechanics. This gap is filled in actual scientific practice by invoking the conscious intentions of the human participants. This practical and intuitively felt role of conscious intentions is elevated, within the proposed quantum ontology, to the status of an ontological reality coherently and consistently integrated into quantum laws.

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References

Bohr, N.: 1935, 'Can quantum mechanical description of physical be considered complete?', Physical Review 48, 696-702.

Bohr, N.: 1958, Atomic Physics and Human Knowledge, New York: Wiley.

Bohr, N.: 1963, Essays 1958/1962 on Atomic Physics and Human Knowledge, New York: Wiley.

Einstein, A., Podolsky, B. & Rosen, N.: 1935, 'Can quantum mechanical description of physical be considered complete?', Physical Review 47, 777-780.

Einstein, A.: 1951, 'Remarks to the essays appearing in this collected volume', in: P. A. Schilpp (ed.), Albert Einstein: Philosopher-Physicist.
New York: Tudor.

Libet, B.: 1985, 'Unconscious cerebral initiative and the role of conscious will in voluntary action', Behavioural & Brain Sciences, 8, 529-566.

Libet, B.: 2003, 'Cerebral physiology of conscious experience: Experimental Studies', in: N. Osaka (ed.), *Neural Basis of Consciousness*. [Advances in consciousness research series, 49] Amsterdam & New York: John Benjamins.

James, W.: 1892, Psychology: the briefer course, in William James: Writings 1879-1899. New York: Library of America.

James, W.: 1911, 'Some Problems in Philosophy', in William James; Writings 1902-1910. New York: Library of America.

Rosenfeld, L.: 1967: In Wheeler and Zurek (eds.), Quantum theory and measurement. Princeton N.J.: Princeton University Press.

Schwartz, J., Stapp, H. & Beauregard, M.: 2005, ' Quantum physics in neuroscience and psychology: a neurophysical model of mind/brain interaction', Phil. Trans. Royal Society: B 360 (1458) 1308-27.
(http://www-physics.lbl.gov/~stapp/PTRS.pdf)

Schwinger, J.: 1951, 'Theory of quantized fields I', Physical Review 82, 914-27.

Stapp, H.P.: 2002, The basis problem in many-worlds theories, Canadian Journal of Physics 80, 1043-1052.

Stapp, H.P.: 2004a, Mind, Matter, and Quantum Mechanics (Second Edition), Berlin, Heidelberg, New York: Springer.

Stapp, H.P.: 2004b, 'A Bell-type theorem without hidden variables', American Journal of Physics 72, 30-33.

Stapp, H.P.: 2005: 'Quantum Interactive Dualism: An Alternative to Materialism', Journal of Consciousness Studies, 12, No. 11, 43-58.

Stapp, H. P. 2006a: ‘Quantum Approaches to Consciousness’, in M. Moskovitch and P. Zelago (eds.), Cambridge Handbook of Consciousness, Cambridge: Cambridge U.P.
(http://www-physics.lbl.gov/~stapp/stappfiles.html)

Stapp, H. P.: 2006b, ‘Quantum Mechanical Theories of Consciousness’, in M. Velmans and S. Schneider (eds.), Blackwell Companion to Consciousness, Oxford: Blackwell Publishers.
(http://www-physics.lbl.gov/~stapp/stappfiles.html)

Stapp, H.P.: 2006c: ‘The Quest for Consciousness: A Quantum Neurobiological Approach’, see http://www-physics.lbl.gov/~stapp/Quest.pdf

Stapp, H.P.: 2006d, Mindful Universe, see
(http://www-physics.lbl.gov/~stapp/MU.pdf)

Tomonaga, S. 1946: ‘On a relativistically invariant formulation of the quantum theory of wave fields’, Progress of Theoretical Physics 1: 27-42.

Von Neumann, J.: 1955/1932, ‘Mathematical Foundations of Quantum Mechanics’. Princeton: Princeton University Press. (Translated by Robert T. Beyer from the 1932 German original, Mathematiche Grundlagen der Quantummechanik. Berlin: J. Springer).