What is an Essentially Quantum Mechanical Effect?

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Abstract

When asking whether consciousness is an "essentially quantum effect", one must first lay down criteria for considering an effect quantum mechanical. After a brief survey of the interpretations of quantum theory, three such sufficient criteria are proposed and examined: wave-particle duality (or collapse), entanglement ("non-locality"), and quantum condensation (involving "identical" particles). A fourth criteria could involve the use of quantum field theories, but this problem is left open. If a quantum effect played an essential role in the brain, it would probably follow the first criterion, since the entanglement of many particles would be rapidly washed out by decoherence, and there is no strong evidence for the existence of biological condensates.

1. Prologue

In the last decade, many thinkers have defended the view that the mind-brain problem can only be solved if one takes into account the quantum-mechanical nature of the brain (Hameroff & Penrose 1996). In opposition to them, many others have sustained the "astonishing hypothesis" that the mind results from the organization of matter and energy in the brain, in a way that does not involve any essentially quantum mechanical effect (Crick 1994; Grush & Churchland 1995). Without having to take sides here in this ultimately empirical question, I would like to examine the issue of what is the meaning of the notion of an "essentially quantum effect" (1).

To simplify the discussion, let us adopt a physicalist (materialist) view of the mind-brain issue, although the consequences drawn here might be adapted to a dualist view. In this physicalist framework, most everyone agrees that the brain is, in some trivial way, a quantum mechanical system, since it consists of heptillions of interacting atoms, and by the usual standards an atom *is* considered a quantum system.

2. Interpretations of Quantum Theory

At this point it might be important to draw the distinction between ontological and epistemological assertions. If we write that "an atom *is* a quantum system", this is usually understood as an assertion about a real entity, the thing in itself, and in this sense it is an ontological assertion. In contrast to this, an epistemological statement expresses our *knowledge* of an object. Examples could be "an atom is understood as a quantum system", "an atom appears as a quantum system", "quantum physics may be adequately applied to the description of an atom", etc.

Quantum theory describes in a detailed and adequate way a huge number of observations, and there is a consensus that it is an extremely good theory. However, the formalism of quantum mechanics is consistent with many different conceptions of the nature of the reality that underlies these observations (there is an "underdetermination" of the observations by the non-observational terms of the theory). This situation is usually called the problem of "interpretation" of the theory (2). Quantum theory can be interpreted in many different ways, and the present author has counted at least fifty different proposed interpretations! To classify these interpretations, the first line to be drawn is between realist and positivist views.

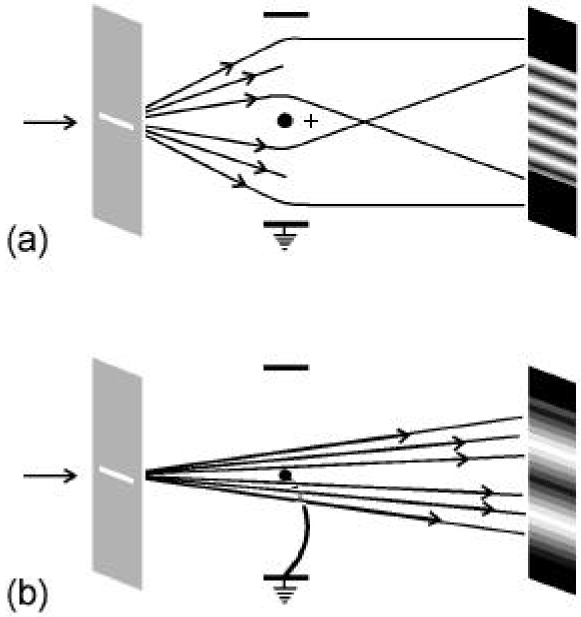
In the context of philosophy of physics, the term "positivism" denotes the attitude of withholding any statement about unobservable entities. A positivist does not necessarily deny that there exists a reality behind the observations, but he denies that it makes sense to claim that a physical theory correctly describes this unobserved reality. Any physical theory is constructed specifically to account for observable data, so it would be naïve (according to this view) to extrapolate to the unobservable. In the case of quantum theory, the situation is far more serious than in classical physics, because any attempt of postulating an underlying reality leads to counterintuitive conclusions. The orthodox interpretation of quantum mechanics (so-called "Copenhagen", due to Niels Bohr, Werner Heisenberg, and Wolfgang Pauli) is basically positivistic, although it does have one specific realist trait, which is the claim about the existence of certain symmetries (involving the coordinate and the momentum representations). If one wants to use Bohr's definition of a "wave phenomenon" and a "corpuscular phenomenon", one must only apply them only *after* an observation has been made, never before (not because of lack of knowledge, but because such traits remain undefined until the measurement is completed).

Realist interpretations claim that a description of reality can be made at every instant, even in between observations. The description of reality does not depend in an essential way on the presence of an observer, even though his presence may affect the quantum object in an uncontrollable way (after all, the observer *is* part of reality). There are basically three main groups of realist interpretations, depending on the ontology that is assumed: (i) Wave interpretations ascribe reality to the wave function $y(\mathbf{r})$ or to a state vector, even though such function in general is defined in high dimensional spaces. One may either assume that real non-local stochastic collapses of the wave take place, or might try to explain this in some way (such as in the many-worlds interpretation of Hugh Everett). (ii) Corpuscular views are usually implicit in the so-called ensemble interpretation of quantum mechanics, and has been courageously defended by Alfred Landé. Yet, a strictly corpuscular interpretation has difficulty in explaining interference, although one may take recourse to non-classical logic. (iii) A combination of both ontologies has been developed by Louis de Broglie and David Bohm, in what might be called a dualist (3) realist interpretation (better known as the "pilot wave interpretation"). Non-local collapses seemed at first to be avoided at the expense of having to postulate "empty waves" (which exist in spite of being unobservable), but Bohm made it clear that his interpretation is *non-local* when measurements are made on one of two "entangled" particles.

We will postpone further discussion of non-locality and entanglement to section 6.

3. First criterion: Wave -Particle Duality

Returning to our prologue, the problem is to define what is an "essentially quantum effect". To do this, we can start out by giving an example of a system that is clearly quantum-mechanical: a beam of electrons. In 1955, Möllenstedt & Düker performed an experiment (called "electron biprism"; for a recent survey see Hasselbach 1992) in which a spread-out beam of electrons passed on both sides of a positively charged wire (Fig. 1a). Electrons that pass on either side of the wire are attracted by it. The overall effect is a recombination on the detection screen of the amplitudes passing on each side. What both scientists observed on the screen were clear interference patterns, which is typical of waves. One could then apply classical wave mechanics to explain the result of the experiment.



But there is a hitch. Electrons are detected as discrete particles. If Möllenstedt & Düker could have distinguished individual electrons, they would have seen that the interference pattern is built slowly, by accumulation of the individual point-like marks on the screen. This in fact has been directly observed in the 1980's. So in a sense electrons behave as waves, but they also behave as particles. This might be considered an expression of the "wave-particle duality" – a weak form, which is different from the stronger form that Bohr called "complementarity" (which involves trajectories, and not simply point-like marks; for further discussion, see Pessoa 2000). This *wave-particle duality* is the basic signature of a quantum-mechanical effect.

Now suppose that the wire is grounded and loses its charge (Fig. 1b). The wire will now only cast a shadow on the screen, and what will appear on the screen will be two distinct regions in which the electrons fall (4). For an electron that falls on the upper region, we can safely say that it passed above the wire. In other words, trajectories may be ascribed to the electrons, which therefore behave as classical particles. So *this* effect (contrary to the preceding one) is *not* essentially quantum-mechanical, because it can be understood in terms of classical particle physics.

Switching to a realist language, we could say that a beam of electrons is a quantum mechanical *system* or *entity* because there exists an experiment that can be made on it which turns out being an essentially quantum effect. Notice, however, that an aggregate of quantum systems (such as a planet) could turn out not exhibiting any quantum effect, that is, could turn out not being itself a quantum system. To avoid such problems (which are nevertheless interesting), we will stick to our definition of "quantum effect" and not use for now the realist terminology referring to "systems".

Wrapping things up, we have considered three different kinds of effects: (i) The electron biprism in which individual electrons can be distinguished in an essentially quantum effect (5); (ii) When the wire is grounded, there is no more interference pattern, trajectories of each detected electron may be ascertained, and the effect is not essentially quantum mechanical: it may be described by classical particle physics; (iii) How about an effect that is *not* essentially quantum mechanical, but is described by classical *wave* mechanics? In our example, this would correspond to the electron biprism setup in which individual electrons are *not* distinguished in the detection screen.

This last example is interesting because it indicates how the measurement apparatus is intertwined with the so-called "quantum object", when it comes to defining the type of effect involved (this also happens with Bohr's definition of "phenomenon"). The lack of resolution of the detector renders an otherwise "essentially quantum effect" a classical effect.

This last example is also very instructive for the philosophy of mind. When we try to answer the question of whether consciousness is an essentially quantum effect, we must be clear on who the observer is and what is his "detection resolution". Furthermore, this illustrates the reasonable idea that "what is not a quantum effect may turn out being one if observation is refined".

In summary, our *first criterion* for determining whether a phenomenon is essentially quantum mechanical is *whether it exhibits wave-particle duality*, i.e., whether it cannot be explained solely by classical particle physics or solely by classical wave mechanics (6). This is a sufficient criterion. There might be other sufficient criterion, all of which hinge on the impossibility of furnishing a direct classical explanation.

4. The First Criterion according to the Wave Interpretation: Collapse

One might be wondering how a wave interpretation of quantum theory treats wave-particle duality. Does the wave interpretation employ a classical wave picture? No. The difference is that classical waves evolve in three-dimensional space in a continuous and contiguous manner, while quantum waves suffer instantaneous and non-local *collapses*. The expedient of collapses is the way the wave interpretation introduces the discreteness that is essential in quantum mechanics. Schrödinger, in fact, tried to defend a wave interpretation without collapses, but the consensus has been that he failed.

The upshot of this discussion is that the Schrödinger equation by itself does not render an effect essentially quantum mechanical. The Schrödinger equation is only half of the story told by quantum theory. The other half involves measurement, and what happens when two measurements in succession are performed. If a measurement on a spread-out wave (obeying any equation at all) is followed by a localization of this wave (perhaps in a narrow wave packet), then one may treat such a theory as essentially quantum-mechanical.

Wave-particle duality or collapse will be the only criterion given here for an essentially quantum effect involving a single particle. One may wonder whether other independent criteria could be given, such as the *uncertainty principle*, which we may consider as a restriction on the "resolution" of a single simultaneous measurement of conjugate variables, such as position and momentum (as opposed to the weaker case involving the "precision" or standard deviation of a statistical collection of such measurements). However, the uncertainty principle involving resolutions is also present in classical wave mechanics: a wave packet with a good spatial resolution has necessarily a bad resolution of wavelengths (and vice-versa). The passage from this classical uncertainty principle to the quantum mechanical case involves the introduction of a corpuscular aspect for classical waves, which is precisely the wave-particle duality that we took as our first criterion. For this reason, we do not consider the uncertainty principle as an independent criterion for an essentially quantum effect. The same argument applies to the *tunneling effect*, which has a counterpart in classical wave mechanics.

5. A Simple Example

Consider the detection of individual quanta of light by the retina of frogs. Does this constitute an essentially quantum effect? One might be tempted to say "yes", since we know that, according to 19th century optics, light is considered a wave (which explains interference patterns arising in the two-slit experiment). In the frog's retina each photon may be detected individually, as a particle. This appears to be an example of wave-particle duality. However, in the frog's eye, no interference patterns appear. In this example, a corpuscular model explains perfectly well the detection of light quanta. Therefore, this is *not* an essentially quantum effect. A frog's eye would work appropriately in a classical world in which light is considered a particle (as Isaac Newton did).

Now, even if within the pupil of the frog's eye the waves of light interfered and generated fringes in his retina, still the *workings of the retina* would not be considered an essentially quantum effect, since all it does is register individual (or small groups of) photons, which can always be explained classically by means of particles. In this fictional example, what could be considered an essentially quantum effect would be the workings of the eye as a whole.

6. Second Criterion: Entanglement of Two or more Particles ("Non-locality")

Systems of two correlated ("entangled") particles play an extremely important role in the foundations of quantum mechanics. Such systems were first explored by Heisenberg in 1927, while studying the system of two correlated outer electrons in the helium atom. They were considered by von Weizsäcker (1931) and von Neumann (1932), but only after the famous paper of Einstein, Podolsky and Rosen in 1935 have the peculiar properties of such a system been put to debate, leading more recently to the inequalities derived by John Stuart Bell (1964).

In quantum physics, two or more correlated particles behave in a way that is essentially different from any classical system. We may start with the wave interpretation of quantum theory, and notice that two correlated particles must involve a wave that is defined in a six-dimensional space, instead of the usual three-dimensional space. Heisenberg (1930, p. 47), in fact, defines "classical wave theories" as those limited to three dimensions, so that the following criterion may be proposed: *if the waves involved can only be defined in more than three dimensions, then the effect is essentially quantum mechanical*.

This criterion may be recast in a better known statement if we switch to the realist dualist interpretation of quantum theory. As formulated by Louis de Broglie, the particle's trajectory is guided by the associated wave, which is basically the same as the one postulated by the wave interpretation. David Bohm (1952) discovered that for two entangled particles (such as the ones postulated by Einstein, Podolsky and Rosen), according to this dualist interpretation, the measurement on one of the particles exerts a non-local (instantaneous) causal influence on the other particle. In more precise terms: the measurement outcome on one of the particles alters instantaneously the quantum potential (the wave) associated to the other far-away particle, so that the particle may aquire a new trajectory (due to the alteration in its associated guiding wave).

John Bell generalized this result showing that a very large class of *local realist* theories are inconsistent with quantum mechanics, and, as later shown, also with experiment. At first, local realist theories satisfying a statistical constraint known as "induction" (which includes fair sampling) and satisfying "determinism in measurements" (the value of real entities determines uniquely the outcome of measurements) were shown to be inconsistent with quantum mechanics.

In the 1970's, this proof was generalized for theories that don't necessarily satisfy determinism in measurements. Such generalized class is known as "stochastic hidden variables theories". Although different interpretations of this result are possible, the conclusion that is more widely accepted is that realist theories satisfying (induction and) a "controllable" locality are tenable, as long as an "uncontrollable" locality is violated. This latter condition, also called "outcome independence", asserts that the outcome obtained for the second particle depends on the outcome obtained for the first (Jarrett 1984).

One advantage of this formulation, in comparison with Bohm's, is that one does not have to speak of a *causal influence* from one particle to another. Bohm's theory is non-relativistic (as is the quantum mechanics described by the Schrödinger equation), so the existence of non-local causal influences does not lead to paradoxes (there is a privileged reference frame in which space-like separated events are temporally ordered in a unique way). However, since we must accept special relativity, we therefore should be worried about the possibility of non-local causal influences (signal propagation).

The violation of "outcome independence" may be interpreted as forcing upon us the following conclusion: measurements performed on two separated particles in an entangled state furnish outcomes that are *correlated*, although there is *no causal influence* between the two. The reason why one of the measurement outcomes cannot be considered the cause of the other is given by special relativity: there is a reference frame in which measurement 1 is performed *before* measurement 2, and another frame in which this order is inverted (because the events are "space-like separated", one being outside the light cone of the other).

Furthermore, the *correlation* cannot be fully explained by a "common cause", as would be the case in classical physics. One might say that the *existence* of a correlation can be explained by a common cause, which produced the pair of entangled particles (in the case of photons, either in an atomic cascade or in a non-linear crystal). However, the fact that *a specific pair* I_n, II_n, of correlated outcomes came up (and not another possible pair) *cannot* be explained by a common cause. This is the philosophical content of Bell's theorem.

This situation might be appropriately described by the term "synchronicity": the values of the outcomes are correlated but the "choice" of their values has no common cause, and one does not cause the other. This term, however, should in no way support the use of the word "synchronicity" made by the psychoanalyst Carl Jung, which loads this term with questionable mystical implications.

When the expression "non-locality" is used as a signature of an essentially quantum effect, what is meant are the subtle distinctions made in the preceding paragraphs. From the general point of view of stochastic realist theories, non-locality refers to the violation of "outcome independence". From the point of view of a realist theory with "determinism in measurments", such as Bohm's interpretation (which however lacks relativistic covariance), non-locality denotes true action at a distance, that is, instantaneous causal influences over great distances.

There is an elegant way of determining whether a system of correlated particles exhibits non-locality. One represents the state of the system in phase space, according to the Wigner-representation, and if there are *negative probabilities*, then the system may be considered non-local. In other words, negative probabilities (which measure the "degree of impossibility" of a situation) are a special case of the second criterion (involving correlated systems of particles) of an essentially quantum mechanical effect.

7. Decoherence

The best known attempt to base consciousness on an essentially quantum effect is the proposal of Hameroff & Penrose (1996) that the subcellular cytoskeleton of neurons may process information in a quantum mechanical fashion, involving superpositions or even entanglement. The protein microtubules which form the cytoskeleton are cylinders with a diameter of 25 nanometers (1 nm = 10^{-9} m), the precise description of which probably requires quantum theory. However, there is no convincing evidence that such microtubules process information in any way that resembles "quantum computers".

Quantum computation has been described theoretically in the last fifteen years, and it has been shown that if a desktop quantum computer could be constructed, it would be able to find the prime factors of the huge numbers used in cryptography, therefore rendering present-day security systems obsolete. However, there are very serious technological limitations for the construction of such computers, which depend on the entanglement of a large number of particles.

The interaction of the particles with their environment tends to destroy their “coherence”, which means that their entanglement is broken. This process is called “environmentally-induced decoherence”, or simply “decoherence”. A single particle may be subject to decoherence, which destroys its capacity of interfering with itself. Every time a collapse takes place, decoherence also takes place: the environment in this case is the macroscopic apparatus which interacts with the particle. Yet, the converse is not always true: a system subject to decoherence does not lead necessarily to the collapse of its state to one of its possible outcomes (for a fuller discussion of decoherence, see Pessoa 1998a).

The question of whether a quantum computer of a reasonable size can be constructed depends on many technological issues, such as error-correcting mechanisms, and is only viable at low temperatures, when fluctuations form the environment are minimized. In view of this situation, it is highly improbable that a similar mechanism may exist in the human brain. Even the entanglement of two particles in a neuron would be hard to shield from the surrounding heat sources in the brain (such particles would not fly freely in the air as those mentioned in the previous section in the tests of Bell’s theorem). The greater the number of entangled particles, the harder it is to maintain their coherence.

For this reason, if there were a quantum effect which is essential for consciousness, the chances would be greater that it follow the first criterion mentioned above (wave-particle duality) and not the second (entanglement).

8. Third Criterion: Quantum Condensates

Bose-Einstein condensates constitute a third essentially quantum effect which depends on the so-called property of “indistinguishability” of identical particles. At low temperatures, the class of particles called “bosons” (characterized by integer spins, as opposed to “fermions” which have half-integer spins) tend to condense all into the same quantum ground state, as if they lost their individuality, having their wavefunctions spread out to cover the other particles’ wavefunctions. The problem of philosophically interpreting identical particles and condensation still has conceptual problems, but this of course does not hinder the development of physical theory and experiment.

In recent years, Bose-Einstein condensates have been produced with sodium atoms (and also others), exhibiting the collective behavior that the spins of all the particles point in the same direction. The ground state in this case is “degenerate”, meaning that different collective spin states are possible, all with the same energy. This property is also known as “long-range order”, but it should *not* be confused with non-locality. The maintenance of order does not take place instantaneously: if one atom were forced into a certain spin state, the other particles could end up pointing in that same direction, but this would take a finite length of time. That this must be true follows from the impossibility of sending “signals” instantaneously.

The third criterion has been associated to the collective behavior of bosons, but it may be traced back to the property of “indistinguishability” of identical particles, and associated to any effect which depends on this property. Turning to fermions, one might characterize the collective behavior in an “electron gas” (which exists in metals) as being essentially quantum mechanical, although this claim deserves further examination. One might also consider Pauli’s exclusion principle – associated to the fact that electrons don’t all fall to the same ground state – as fulfilling this third criterion.

9. Biological Condensates

Herbert Fröhlich (1968), of the University of Liverpool, proposed a model which indicated that it is possible for biological systems at room temperature to be in a state which is similar to Bose-Einstein condensates, involving long-range order (phase coherence). There is, however, one basic difference between the two types of condensates. Bose-Einstein condensation occurs in a state of thermodynamic equilibrium, when it is possible, at a given low temperature, to control the density of the particles by means of the so-called "chemical potential". On the other hand, the biological condensate proposed by Fröhlich involves *phonons*, the quanta associated to normal modes of oscillation, which have mass zero and therefore also zero chemical potential. Because of this difference, one cannot have condensation in a situation of equilibrium for a system of massless bosons.

Fröhlich's idea was to construct a different physical situation in which something analogous to the chemical potential would arise. This he achieved for a system far from equilibrium surrounded by a thermal bath, with the presence of a non-thermal energy source, in a stationary regime (meaning that the energy of the system is constant). For this situation, he showed that for a fixed temperature there is a value for the energy (furnished by the source) which leads to a macroscopic occupation of the "zeroth mode", the ground state of each phonon.

Fröhlich proposed his model initially for cellular membranes, involving electric dipole (hydrophobic proteins) which would vibrate (in the zeroth mode) at a frequency around 10^{12} hertz. He speculated that such oscillations could play a role in cellular reproduction or, at least, constitute a biological reservoir of energy in an ordered form.

Those who share the view that quantum effects play an essential role in giving rise to consciousness usually mention the possibility that a Fröhlich type biological condensate may play an essential role in binding the activity of the brain (Marshall 1989). However, the evidence often-mentioned (Penrose & Hameroff 1996, p. 517) is far from conclusive. Even the existence of Fröhlich condensates in other biological systems has not yet been confirmed, which is curious state of affairs, since the model is correct and therefore could in principle be artificially constructed (Lockwood 1989, p. 259).

In contrast, there is some body of evidence that mental states of awareness are associated to oscillations of 40 to 60 hertz, which arise in a synchronized manner in different regions of the brain. Classical models that claim to explain these oscillations have been proposed in the literature (see Robinson *et al.*1998).

A problem that any physical model of consciousness must clarify in advance is what is the physical property one wishes to derive (7). What is the physical analog of consciousness? For example, a physical model that explains the solidification of water must stipulate clearly what are the characteristic properties of a solid (such as a periodic crystalline structure, etc.). But what are the properties that a physical model of consciousness should satisfy? Clearly, phase coherence or long range order is not sufficient.

10. Models based on Quantum Field Theory

In the 1960's, Karl Pribram proposed a "holonomic" model of the brain (see Pribram 1991), which led to the mathematical approach initiated by Stuart *et al.* (1979) of modeling brain functions as a continuous "dendritic field", over and above the conventional dynamics of neurons and synapses. The mathematical formalism that is used are the equations of quantum field theory, which associates to each point in space quantized oscillators (instead of classical oscillators, as in classical fields). Jibu *et al.* (1996) associate memory to "Goldstone bosons", while long range order would arise by "superradiance", with pulses of "solitons" being maintained by "self-induced transparency".

Such use of quantum field theory in these examples is clearly speculative and far-fetched, with no hint on how to test them experimentally. However, one should not dismiss such attempts so hastily. The language of quantum field theory has very interesting features: it may be considered a general, a priori, mathematical language, the physical content of which only arises after specific symmetries are stipulated (Auyang 1995; Jackiw 1997). Due to this generality, it could turn out to be a useful mathematical framework in fields outside of physics.

When there are many bosonic quanta associated to each space-time point, quantum field theory may converge to the classical wave description. Because of this, the use of the language of quantum field theory by itself does not render an effect essentially quantum mechanical. One might then ask whether theories such as that of Jibu *et al.* describe essentially quantum mechanical effects (independently of the plausibility of such models). Werbos (1993, pp. 301-3) has argued that this is not the case, even if brain functions be adequately described by equations analogous to those of quantum field theory. One might claim that their theory is a classical wave model, inasmuch as one cannot detect individual quanta of the alleged quantum mechanical field. However, I shall leave this problem open for now, due to my lack of knowledge on the subject, including on the issue of what conditions must be satisfied by a quantum field theory for it to be considered "essentially quantum mechanical".

11. Quantum-Like Theories

One may notice that the criteria that have been proposed don't depend on the details of the quantum mechanical laws. If a new theory is proposed in which Schrödinger's equation is modified (for instance, to satisfy special relativity, as was first done by Dirac), it may still satisfy one or more of the three criteria suggested in sections 4, 6, and 8. There is a large class of theories, which are "non-classical", or "quantum-like" (8). How are such quantum-like theories to be defined?

One approach is to interpret the structure of quantum theory as consisting of a level of "potentialities" and a level of "actualizations", to use the Aristotelian terminology. Abner Shimony used these terms to characterize the collapse of the wave function as an "actualization of potentialities". Wave functions are potentialities, measurement outcomes are actualizations. Potentialities evolve in time according to dynamical laws (such as Schrödinger's equation), while statistical rules describe the passage from potentialities to actualizations. The aim of such scientific theories is to describe correctly the actualizations and their probabilities, while no constraint has to be imposed on the nature of potentialities (besides furnishing correct actualizations). Quantum-like theories might be defined as a class of potentiality theories in which the actualizations are point-like events (while the potentialities are not).

Potentiality theories are more powerful than theories restricted to actualizations (such as classical physics). They might be useful in psychology and sociology, even if no reality were ascribed to the level of potentialities. In psychology, for example, the unconscious may play the role of potentialities. What would be needed, in this case, is, first, a stipulation of the laws or rules describing the structure of the potentiality and its temporal evolution and, second, a determination of what are the relevant actualizations and the (probably statistical) rules describing the passage of a potentiality to an actualization.

12. Conclusion

We have proposed and examined three sufficient criteria for an effect being considered "essentially quantum mechanical": wave-particle duality (or collapse) for a single particle, entanglement (non-locality) for two or more particles, and quantum condensation for a large collection of identical particles. A fourth independent criterion could arise from quantum field theory (but this problem has been left open).

We have adopted a physicalist point of view, which considers that mind, consciousness, awareness, qualia, etc. *can* be explained in the framework of the natural sciences. If this is correct, then we may assume that someday a scientific theory of the mind will be accepted. Will this theory be essentially quantum mechanical? The answer will depend on empirical results, but while we still don't know, philosophers should try to understand at least *what it means* to be "essentially quantum mechanical". This was the aim of this paper.

In sections 7 and 8, I have argued against the thesis that the unity of consciousness arises from non-locality or from quantum condensation. It seems to me that the coupling of networks of classical oscillators is sufficient to give rise to the synchronism of the brain. The conceptually hard problem seems to be qualia, not binding. I would say that if quantum mechanics play any essential role in giving rise to consciousness, it would be according to the first criterion.

Yet, I see no evidence for the claim that consciousness is an essentially quantum effect. What I do see in most defenders of quantum consciousness is a mystical or even religious feeling that compels them to believe that we are more than the complex soft machines that reductionist science is telling us we are.

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Notes:

(1) Throughout this paper we will be using the expression "essentially quantum mechanical effect", or "essentially quantum effect" for short. Maybe a more appropriate expression would be "essentially quantum phenomenon", but the term "phenomenon" in the philosophy of quantum mechanics has already a peculiar sense given by Niels Bohr.

(2) In this paper, I will omit references to the different conceptual problems of quantum mechanics and to specific interpretations proposed by different authors, which may be gathered for example in Jammer (1974). In Portuguese, a conceptual introduction to quantum theory and its interpretations may be found in Pessoa (1997, 1998b).

(3) This dualism (wave/particle) has nothing to do with the dualism (brain/soul) in the mind-body problem.

(4) Any diffractive effects, occurring on the border of the regions where the electrons fall on the screen, will be neglected. Such diffraction would not arise from interference *between* the two beams, but from interference *within* a single beam (which does not affect our inference concerning which path a detected electron took). If one of the beams were completely blocked off, such diffractive effects on the other beam would not be affected.

(5) This class corresponds to what Bohr called a quantum-mechanical "wave phenomenon".

(6) Notice that this wave-particle "duality" has a different meaning from de Broglie and Bohm's "dualist" interpretation. The latter dualism consists of a realist explanation of the appearance of wave-particle duality. Other realist explanations of this appearance (such as the wave interpretation) are also possible.

(7) This remark, which may be found in the literature, was made to me by Carla Goldman, who conducted a discussion on biological condensates at the Institute of Physics, University of São Paulo. See the summary of the discussion, in Portuguese, at http://www.fis.ufba.br/dfg/pice/ff/ff-22.htm .

(8) This class apparently excludes semi-classical theories such as the WKB-approximation and the Jaynes-Cummings model.

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