123-A1675 5/30/2001 3:07 PM Page 87

B. J. HILEY
Physics Department
Birkbeck College, University of London
London, WC1E 7HX, United Kingdom

In this chapter, I discuss various views of the role of the observer in quantum mechanics and then examine the possibility that quantum mechanics plays a key role in describing the relation between mind and matter in the brain. The proposals for such a connection made by Beck and Eccles and by Penrose are examined in the light of Bohm's notion of the implicate order through which it is possible to consider mind and matter as different aspects of the same deeper underlying process. The consequences of this approach are highlighted.

Particles, Fields, and Observers

Introduction

With the appearance of quantum phenomena, the classical paradigm that had served the world of Newtonian physics so successfully was forced to undergo a radical transformation. The traditional methods of describing physical processes were called into question, including the notion that there was an objective real world out there and the aim of physics was to provide an account of this world in a way that was independent of how it was observed. In other words, the physical processes were assumed to be independent of the means of observation and a purely objective description of the phenomena was the only acceptable form of theory. Within the classical scheme, our instruments do interact with the system under investigation, and the interaction will produce some changes in the system under investigation. This was never denied, but it was assumed that the effects of our instruments could be reduced to a minimum by ingenious design of our measuring instruments. Even if the last traces of the instrumental effects could not be reduced further, it was assumed that these effects could be allowed for by suitable calculations. Thus, the theory would stand independent of the observer and his or her instruments.

The basic elements within this classical paradigm were the particle and the field. The particle was assumed to be an independent entity that occupied a local region of space and could be isolated from its environment. It possessed intrinsic properties, such as mass and charge, by means of which we could identify it. To understand more complex systems, it was simply a matter of finding the forces between the individual particles that comprised the system, studying their interactions in detail, and then predicting their subsequent behavior. The attempts to treat these forces as a direct interaction between the particles failed and the notion of a field from which the forces could be derived provided the most powerful and consistent way for accounting for this coordinated movement. Not only could we account for the physical properties of the macroscopic world of our immediate surroundings but also we could account for the movement of the planets and the stars in the heavens. Using simple laws, predictions as to what would happen in given situations could be made with certainty. In this role the physicist appeared as a modern powerful soothsayer—he or she could not only predict future behavior of matter but also change his or her environment by using this knowledge.

As a system became more complex, it was much more difficult to calculate exactly the resulting behavior, but such difficulties were not regarded as calling for a change in fundamental outlook. The difficulties could simply be attributed to the technical problems of solving the set of complex mathematical equations. Chaotic systems produced surprises when it was discovered that simply by changing parameters what appeared chaotic suddenly becomes ordered and what appeared ordered could become chaotic. These features were unexpected, but they should not have been too surprising because the techniques for investigating these systems were not available until the advent of user-friendly computers. Until then people only investigated equations of motion that were simple to solve analytically, or when it was necessary to resort to numerical solutions only simple cases could be solved and these often involved long and tedious calculations. It was the computer that opened up a new world for us, but this world was still objective and independent of the observer and the means of observation.

The Quantum World

Quantum mechanics challenged this whole way of thinking. Reductionism had been at the heart of classical thinking, but in the quantum domain there were things going on in the physical world that seemed to deny reductionism. In order to bring out the nature of these radical changes, it is necessary to first explain how quantum mechanics works. Once there is some understanding of this, we will then discuss the full implications of the quantum domain.

In the conventional approach to quantum mechanics, the uncertainty principle plays a central role. This principle is taken to imply that it is no longer possible to describe a particle in terms of its precise position and precise momentum at every instant of time, thus denying the possibility of following a particle along a well-defined trajectory. In fact, the uncertainty principle arises from the analysis of an attempt to measure the position and momentum of a particle together. The usual way of presenting the argument is based on the Heisenberg γ-ray microscope shown in Fig. 1.

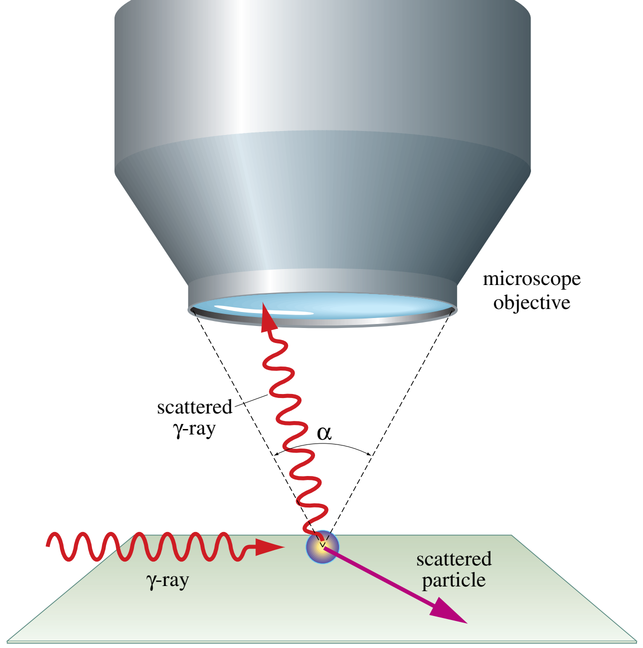

FIGURE 1 The Heisenberg γ-ray microscope used to illustrate the ideas of the uncertainty principle. The observed particle (violet sphere) is placed directly under the microscope objective from where the lens is seen as a circle at the base of a cone of angle α. It is then illuminated by a γ-ray from the left. At the moment when the γ-ray is diffused into the objective of the microscope, the particle moves to the right.

Consider a high-powered microscope that is used to measure the position of a very small object to a high accuracy. Suppose the object is a small spherical molecule. To determine what conditions are required to obtain a high resolution we need to know the expression for the smallest distance that can be resolved. When the microscope is illuminated by light of wavelength λ, the smallest resolvable distance, Δx, is given by

$$\Delta x \approx \lambda/\sin\alpha, \qquad [1]$$

where α is the angle subtended by the object at the objective lens of the microscope. Thus, to obtain a high resolution it is necessary to illuminate the object with light of the shortest possible wavelength. Heisenberg (1958) suggested that the maximum resolution could be obtained by using light in the form of γ-rays in which the wavelength is very small.

The object is seen by scattering the light off the object and collecting it in the image plane of the microscope. If γ-ray wavelengths are used, the molecule is given a considerable impulse and therefore moves in some direction, whereas the γ-rays are deflected into the lens of the microscope. To minimize this disturbance, the intensity of the illuminating beam must be reduced. Consider the effect of a collision of the atom with a single γ-ray. The molecule will move off with some momentum *p,* whereas the γ-ray will enter the objective lens of the microscope. If we know the precise direction in which the γ-ray entered the microscope, we could calculate the scattered direction of the particle. This would enable us to calculate the momentum of the particle and therefore no uncertainty in the momentum of the scattered atom would result. However, in order to find the direction of the scattered γ-ray we need to know precisely the angle at which the γ-ray enters the microscope lens. Because the lens subtends an angle α at the object, the γ-ray entry angle is uncertain and this leaves an uncertainty in the momentum of the molecule, Δp, which is given by

$$\Delta p \approx p \sin\alpha. \qquad [2]$$

We can make Δp small by making the lens aperture as small as possible and thus we need to make α small. However, as α is made small, the accuracy of the initial position of the particle, Δx, will become worse as can be seen from Eq. (1). Thus, to determine the momentum of the scattered particle accurately, we have to make α small, but to find the position accurately we have to make α large. Combining the two expressions yields

$$\Delta x \Delta p \approx \lambda p. \qquad [3]$$

If we use the de Broglie relation $p = \hbar/\lambda$, where $\hbar$ is Planck's constant, then we obtain the expression

$$\Delta x \Delta p \approx \hbar. \qquad [4]$$

Since $\hbar$ is a universal constant, there is a universal limit on the accuracy within which we can measure position and momentum simultaneously.

These are not the only variables that are subjected to an uncertainty principle. It is possible to find sets of variables that cannot be measured at the same time as other sets of variables. In other words, it is only possible to get exact information about the variables in one compatible subset, with the remainder being undetermined. Thus, there is a universal limit on the information that we can obtain from any set of measurements. Consequently, unlike in the classical world, we can no longer expect to obtain a complete, precise, and unambiguous account of physical processes.

Bohr (1961) was the first to recognize the physical and philosophical implications of these results. He regarded the uncertainty principle as meaning that it was no longer possible to maintain a sharp separation between the observer and his or her means of observation. It was as if there was an "indivisible link" between the two sides so that they formed an indivisible and unanalyzable whole. Without sharp separation, we cannot say what property belonged to the observed system and what property belonged to the observing apparatus. He illustrated the problem by liking it to a blind man probing an unknown room with a soft rubber stick. If the stick were rigid, a blind man could use it to obtain a clear picture of the room and its content. However, if he used a rubber stick he would at best get an hazy idea of the layout of the room. Thus it is with quantum phenomena. How then was it possible to do science in this situation?

Classical physics regarded the state of a system as being defined in terms of some function of the position and momentum. Given the initial conditions and the interaction forces between the particles, Newton's laws of motion took care of the rest. For quantum phenomena, since knowledge of the position and momentum of the particle are limited by the uncertainty principle, the classical description could no longer be used. Instead, it is necessary to introduce a wavefunction, $\psi(\boldsymbol{r}, t)$, which is a function of position and time, to describe the system. From this function it is possible to determine the properties of the system using a well-defined set of rules so that these properties can be determined without violating the uncertainty principle. The wavefunction is generally a function of position and time, or of momentum and time — one being the Fourier transformation of the other. The position representation is more generally used in an attempt to offer an explanation of quantum mechanics. The important point to note is that it cannot be a function of both position and momentum at the same time because this would lead to results that would violate the uncertainty principle.

If the wavefunction is in the form of a packet and this packet is spread over a narrow region, then the position of the particle is sharply defined. If it is any other function then we can only know the probability of finding the particle at a certain point. Even when the wavefunction is only a function of position, we can obtain some information about the momentum. However, this information is ambiguous in the sense that we can only predict the probability of finding a particular value of momentum should we perform the appropriate measurement. Thus, the quantum formalism provides us with only ambiguous information about the properties of the particles so our goal of finding a precise and unambiguous description of nature will fail if this view of quantum formalism is used.

We are now faced with an important question of how we do science when the properties are only ambiguous. Does this ambiguity not negate the very possibility of doing science? The answer is no. The wavefunction develops in a well-defined way determined by the Schrödinger equation. For example, for a particle of mass m with wavefunction $\psi(\boldsymbol{r}, t)$ moving in a potential $V(\boldsymbol{r})$, the differential equation takes the form

$$-\frac{\hbar^2}{2m}\nabla^2\psi(\boldsymbol{r}, t) + V(\boldsymbol{r})\psi(\boldsymbol{r}, t) = i\hbar\frac{\partial\psi(\boldsymbol{r}, t)}{\partial t} \qquad [5]$$

At this level the theory remains deterministic. The wavefunction, however, only enables us to predict the probability of finding a particle at a given position. It is these probabilities that are well-defined and completely objective. Our failure to predict the actual outcome is used to argue that quantum mechanics implies that there is a genuine and fundamental indeterminacy in the world. Thus, quantum theory is a statistical theory, but it is not a statistical theory in the ordinary sense. In quantum mechanics, the statistics arise not because we simply have not attempted to find out the detailed properties of the particle but because we cannot know all the details in principle. Despite this apparent limitation on what we can know about the system, quantum mechanics gives vital information about the properties of matter. For example, solutions of the Schrödinger equation provide the exact energy level structures of atoms, molecules, and nuclei and these provide the basis for condensed matter physics, which has laid the foundations of modern computing and information technology.

Despite these successes, there remain some fundamental problems in understanding what it all means. The uncertainties are so small that at the level of everyday experience we can neglect many of these difficulties. As long as we are concerned only with coarse grained averages, we need not use quantum mechanics. However, a word of warning is in order: Some of these quantum effects can be seen at the large-scale level. One striking example of this is in the properties of superconductivity and superfluidity in which, at low temperatures, large-scale electric currents can be made to flow without experiencing any resistance or large quantities of liquid helium can be made to perform tricks that no ordinary liquid would perform. The central question discussed in this chapter concerns the question of whether quantum theory has other surprises for us in areas that we would least expect them.

Before examining these possibilities, we return to the fundamental problems again. As noted previously, the wavefunction evolves in a deterministic manner following the Schrödinger equation, but even within this determinism there are difficulties regarding the properties of particles. There are many situations in which the wavefunction bifurcates into two or more wave packet solutions which do not necessarily overlap in space. Because the Schrödinger equation is linear, each one of these wave packets evolves independently of the others. The formalism provides no answer to the question of which packet contains the particle. We know only that it will be found in one of the packets with a certain probability and that probability is well-defined. The fact that we cannot provide an exact answer to this question has some spectacular consequences.

The best known of these is the Schrödinger cat paradox, first proposed by Schrödinger (1935). A cat is placed in a box so that the cat cannot be seen from the outside. In the box there is a capsule of cyanide gas and a device is rigged so that if a certain event occurs the capsule will be broken and the cat will die. If the event does not occur, then the cat will live. The event that decides the fate of the cat is a quantum event which entails a bifurcation process mentioned previously. We can think of this bifurcation event being produced by a photon striking a half-silvered mirror. This mirror is designed so that any photon has a probability of one-half to be reflected by the mirror and one-half to be transmitted by it. We design the device so that if the photon is transmitted it will activate the mechanism that will break the fatal capsule.

To describe this situation in quantum mechanics, the wavefunction of the photon must be described in two parts — the part that is reflected, $\psi_{\text{reflected}}$, and the part that is transmitted, $\psi_{\text{transmitted}}$. The cat must also be described by a wavefunction, but its wavefunction depends on the wavefunction of the photon. It will be ψ_{alive} if the photon is reflected and ψ_{dead} if the photon is transmitted. The final solution of the Schrödinger equation must be written in the form

$$\psi_{\text{final}} = a\psi_{\text{reflected}}\psi_{\text{alive}} + b\psi_{\text{transmitted}}\psi_{\text{dead}}, \qquad [6]$$

where a and b are constants that take values depending on the precise nature of the mirror. In the case of a half-silvered mirror, they take the same value, $1/\sqrt{2}$. From the previous equation, it can be seen that the final state of the cat is not well-defined. However, if we were to look inside the box after the photon has been emitted, we would see either one or the other possibility. The cat will be either alive or dead. It would never be seen in a state that is both alive and dead at the same time. Therefore, there is a problem. The same problem arises when we replace the cat by a measuring device which, like the cat, is left in a superposition of incompatible classical states, but we only ever see a measuring instrument in a well-defined state. This problem is known as the "measurement problem."

One simple way to avoid this problem is to regard the quantum formalism as nothing more than an algorithm from which we can calculate the probabilities of all the possible outcomes of each experimental situation. However, if we want to regard quantum theory as an objective description of reality, we must regard the wavefunction as describing the state of the system in some way or another. In the situation described previously, there is a problem in that the measuring instrument is not in a well-defined state but we always see it in a definite state. Thus, there is the problem of explaining how the wavefunction collapses to a definite state.

This collapse cannot be described using the Schrödinger equation, so there seems to be two processes occurring in quantum mechanics. One process involves an objective evolution of the wavefunction determined by the Schrödinger equation. The second process involves the actualization of one of the these wavefunctions. It is this latter process that has been the topic of much discussion since it was first presented by von Neumann (1955) in his classic book *The Mathematical Theory of Quantum Mechanics.*

von Neumann's (1955) explanation for the necessity of two distinct processes in quantum theory lies in the very final stages of the observation. That is, it lies in the very process of subjective perception which, he argues, cannot be analyzed further. Initially, t seems that the quantum description should stop at the macroscopic measuring instrument, but as previously mentioned the instrument, like the cat, is still in an ambiguous state. We could proceed further and analyze the light from the instrument entering the observer's retina. Since this is a dynamical process, we must again use the Schrödinger equation. However, because of the linearity of this equation, the image on the retina will still be ambiguous. We could continue this analysis down the optic nerve and even further into the brain, but no matter how far we continue this analysis we will ultimately have to say "a certain result was perceived by the observer." Since according to von Neumann this process cannot be analyzed further, it is necessary to introduce a "cut." On one side of the cut, Schrödinger's equation can be used, whereas on the other side there is simply an inexplicable collapse. The cut therefore divides all processes in two kinds — process 1 (evolution of the Schrödinger equation) and process 2 (the collapse of the wavefunction). In practice, this cut can be placed anywhere outside the measuring instrument without making any difference to the final result.

Wigner's Contribution

Wigner (1986) took the von Neumann argument even further by concluding "It is not possible to formulate the laws of quantum mechanics in a fully consistent way without reference to consciousness" (p. 232).

He had two strands to his argument. The first involves replacing the cat by a friend! However, for humanitarian reasons, the end process does not involve extermination but does involve the friend either seeing or not seeing a flash of light. If the friend is enclosed in the box, the outside observer will conclude at the end of the experiment that his or her friend is in an ambiguous state of both having seen and not having seen the light. However, if the friend is asked to communicate what he or she saw, he or she will always give a definite answer. Since the essential difference between a human and an inanimate measuring instrument is consciousness, Wigner concludes that it is consciousness that necessarily completes quantum mechanics by collapsing the wavefunction.

In order to make his conclusion stronger, Wigner (1986) adds a second strand to his argument. He draws our attention to the principle that to every action there is a reaction. We know that material processes affect the conscious state. For example, a severe loss of body fluids can cause a person to become unconsciousness. If the principle of action and reaction is also valid in this domain, then consciousness must affect matter in some way. There is well-documented evidence that this happens in psychosomatic disorders, so why not extend the idea and propose that it is consciousness that ultimately produces the collapse of the wavefunction?

Two very eminent physicists, who have made significant and fundamental contributions to quantum physics, have both concluded that we must introduce the mind of the observer into the heart of our theories. This is quite an extraordinary situation because physics has always tried to keep the mind out of physics, but quantum mechanics seems to have changed this practice.

A succinct expression of the new relationship between mind and matter as implied by quantum mechanics has been given by Dyson (1979), who has made fundamental contributions to quantum field theory. He points out that awareness of nature seems to enter at two levels. At the highest level, human consciousness is somehow aware of the various physical processes that take place in the brain, whereas according to quantum mechanics, at the lowest level of elementary matter (electrons, atoms, small molecules, etc.) the observer seems to be involved in the description of events in a very basic way. Dyson (1979) concludes

> I cannot help thinking that our awareness of our own brains has something to do with the process which we call "observation" in atomic physics. That is to say, I think our consciousness is not a passive epiphenomenon carried along by the chemical events in our brains, but is an active agent forcing the molecular complexes to make choices between one quantum state and another. In other words, mind is already inherent in every electron, and the processes of human consciousness differ only in degree but not in kind from the processes of choice between quantum states which we call "chance" when they are made by electrons. (p. 249)

I have emphasized the key role that the observer plays in the approach advocated by von Neumann, Wigner, and Dyson because of their historic significance, but I do not want to give the impression that their position is universally accepted by physicists in general. Many physicists find the introduction of any subjective element into the basic laws of physics very disconcerting. Rather than accepting this subjectivity, many physicists would be content simply to use the quantum formalism with its two processes without attempting to resolve the apparent conflict or in the hope that it will be eventually solved in some "acceptable" way. Some would even deny that there is a problem with this situation.

Other Attempts to Solve the Collapse Problem

An important contribution to this general discussion came with the attempt of Everett (1973) to eliminate the human element. He began by questioning the necessity of postulating a collapse in the first place. If this process was regarded as superfluous, it would mean that all the branches of the wavefunction were always present and actual. He writes, "Throughout all of a sequence of observational processes there is only one physical system representing the observer yet there is no single unique state of the observer." Why then do we only see one branch? Everett first proposes, like von Neumann, that the observer perceives himself or herself to be in one branch and only one and is unaware of all the others. Thus, the definite result seen in each experiment depends on which branch the observer is aware of at that particular moment. Here, Everett is, in effect, proposing an interpretation which is based on the possibility of "many awarenesses."

There is still a strong subjective element present, so Everett (1973) makes an additionally proposal, namely, that we can replace a human observer by a machine, one that is sufficiently complex so that statements such as "The machine has perceived A" or "The machine is aware of A" are meaningful. Certainly this would remove the subjective element, but he leaves many vital questions unanswered. For example, there is no explanation of what precisely is meant by "complexity" and when a machine is "sufficiently complex" to be capable of making a perception. Everett's assumption rests on the hope that as we study increasingly complex systems, the answers will emerge. Even if this is satisfactorily resolved, we still have no explanation as to why all observers and machines see one and only one result.

On the question of complexity, there is no denying that present-day investigations of complex systems have revealed that new and exciting properties do emerge, but there is no strong evidence to indicate how awareness could possibly arise in such systems. There is plenty of hope that it will eventually emerge. After all, this is the motivation behind the program known as strong artificial intelligence. However, there are very few compelling results and at this stage it is perhaps best to keep an open mind.

Those who took up Everett's proposal, such as Wheeler (1957) and DeWitt (1971), did not draw attention to the central role played by the notion of "awareness." They tried to provide a more objective explanation of the whole approach. They proposed that all the branches did exist together and that each was regarded to be a different and actual "world." Our experience of a unique world arises because we find ourselves in one particular world with no possibility of gaining information about the other worlds. In one step both objections raised previously are removed. The reason why all observers agree is because they are in this one world and there is no need to raise the difficult notion of awareness.

This modified interpretation was known as the "many worlds" interpretation and was very popular, particularly among physicists working on the quantum gravity program. The study of gravity and general relativity requires us to deal with questions concerning the cosmos, and the collapse induced by measuring instruments seemed to require that the instrument or even the observer must be outside the cosmos, clearly an impossibility by definition. Therefore, the whole discussion within quantum cosmology seems to imply the need for an interpretation of quantum mechanics that can avoid introducing the collapse from the "outside."

There are also difficulties with this interpretation. First, there is a general objection that it needs many inaccessible worlds to exist simultaneously with all but one being unavailable to us. This seems a very extravagant interpretation, but one that may be welcome if it rids physics of the two processes. Unfortunately, it does not. Two processes still remain, but they are now in a modified form. We still have to distinguish those processes in which the world actually divides itself from those processes in which the wavefunction bifurcates, before recombining later to give interference. Recall that the bifurcation in which the world actually divides is needed to resolve the cat paradox, whereas bifurcation that allows recombination is also needed to account for interference.

DeWitt (1971) attempts to resolve this difficulty by suggesting that it is complexity that is the source of this difference. When a system is sufficiently complex, an actual division will occur. Otherwise, the possibility of recombination will remain. However, exactly how complexity will explain the difference is not answered.

There are also other more technical reasons why this interpretation is far from satisfactory. One particular difficulty (discussed later) arises from the fact that there is an ambiguity regarding in which set of basic wavefunctions the actual division takes place. In the formalism, all sets of bases are equivalent, but for the splitting to have an objective meaning one particular basis must be preferred; however, no reason is given as to why one particular basis is to be preferred over any other. Further discussion of this and other more technical difficulties will take us too far from the theme of this chapter so they will not be discussed further. (For more details, see Bohm and Hiley, 1993). As a result of all these problems, this particular interpretation has now dropped out of fashion.

In recent years, the Everett ideas have been taken up by

Murray Gell-Mann (1994) in what he calls the "modern interpretation" of quantum mechanics. This involves, among other things, introducing the notion of "information gathering and utilizing systems" (IGUS) (Gell-Mann and Hartle, 1989). Again, I believe that their discussion is not sufficiently developed to provide a clear account of precisely what new principles are involved in these IGUS. Rather, it is assumed that they exist and the consequences are then further elaborated.

There have also been other developments of the Everett approach in which more emphasis is given to the role played by the human observer. For example, Albert and Loewer (1988) offer a dualist answer that avoids two different physical processes. Like von Neumann and Wigner, they argue that it is the mind that is ultimately the source of what appears to be a collapse. Although all the possible branches of the wavefunction are present in the brain, the mind becomes aware of only one particular branch. Awareness is not a property of a "complex" physical process or a machine — it is a property of mind that cannot be analyzed in physical terms on the assumption that mind lies on the other side of the Cartesian cut where the use of the techniques of science are not valid.

Lockwood (1989) also adopts a similar position but adds the solution to the preferred basis difficulty described previously. He argues that it is our mind that determines a state of the observed system by choosing some preferred frame which is relevant to the brain system. Lockwood offers no explanation as to why one particular basis is preferable over the others, leaving future research into the structure of the brain to provide the answer.

There exists one example of how specific brain structures may provide a connection to the problems discussed previously. Eccles has long advocated a dualist explanation of consciousness. Beck and Eccles (1992) argue that quantum theory provides an answer as to how the intention to carry out a particular task can trigger processes in the brain so as to produce the necessary bodily action to carry out that intention.

To understand their proposals it is necessary to have some understanding of the triggering mechanism of neurons in the brain. A key feature that triggers the transmission of a signal is the onset of exocytosis in the synaptic transmitter. The ion discharge results in a brief excitatory postsynaptic depolarization (EPSP). It is the sum of many such EPSPs that induces an impulse that will travel down the axon, eventually leading to some macroscopic action. The actual process of exocytosis involves the opening of the synaptic vesicle which will produce ion discharge. While the actual opening mechanism is governed by classical physics, the triggering mechanism is understood as being quantum in origin. In the Beck–Eccles model, this process occurs by quasi particle tunneling through a barrier. Once the barrier is breached, the release process is activated. The key new idea is that mental intention can, in some unspecified way, momentarily increase the quantum probability of penetration. Thus, the probability of exocytosis in specific areas of the cortex can be controlled by the mind. By adjusting parameters, Beck and Eccles have produced a model that fits the required experimental data. This explanation is clearly dualist in the sense that mind, which lies outside of the domain of the physical process, influences a physical process in the way suggested by Wigner.

This specific process avoids one of the criticisms of duality made by Dennett (1991). His criticism was that any change in the behavior of a particle in the brain will involve acceleration or deceleration which, in turn, will involve an expenditure of energy. Thus, within the domain of classical physics, any intercession of mind must necessary involve energy transfer. If the laws of physics do not apply to mind, then the intercession of the mind must necessarily imply the nonconservation of energy, a law that is regarded as immutable in these situations. However, in quantum mechanics, energy and time are complementary variables so that when time is well-defined the energy of a system becomes ambiguous; thus, Dennett's specific objection to dualism is no longer as strong as it is in the classical world. Indeed, Beck and Eccles claim that the specific merit of their proposals is that there is no violation of conservation laws. Increasing the probability of penetration need not involve energy loss and therefore Dennett's arguments lose their force.

However, it must be stressed that Beck and Eccles go beyond ordinary quantum mechanics and a new process is being proposed, namely, that transition probabilities in biological systems can be changed in essentially nondynamical ways. This is a very interesting hypothesis and will be discussed later. I will also propose another way of viewing this type of suggestion in the context of a different approach to quantum mechanics in a later section.

Collapse without Observers

The discussions of the previous sections have concentrated on the idea that, in quantum mechanics, the observer must enter physics in a fundamental way. Indeed, the mathematical language uses the term "observable" as one of its basic features and speaks only in terms of measurement. It even goes so far as to deny the possibility of a description of an individual process. Measurement is then the central idea, but as has been mentioned, a description of the actual result of a given measurement is not in the formalism and it is this deficiency that leads to the introduction of an active observer.

Could it be that we have not yet understood sufficiently well what the quantum formalism is trying to tell us about the nature of physical processes and consequently the collapse of the wavefunction is a pseudoproblem in the sense that we have not yet completed the description of quantum processes and that there is still some new physics to be found that will eliminate the need to introduce the mind of the human observer directly into discussion at this fundamental level? Some would even regard the proposals of von Neumann, Wigner, Everett, Albert, Lower, and Lockwood as, at best, misguided attempts to complete the quantum formalism by introducing mind into discussion. Instead, they argue that we should look for different physical explanations as to why the wavefunction collapses in the presence of a measuring instrument.

There have been many attempts to solve this problem without the direct intervention of the observer while staying within the domain of what I call conventional physics. It is not possible, nor indeed would it be appropriate in the context of this chapter, to mention all the attempts that have been made. Many of these attempts have involved introducing some form of nonlinear term, either directly or indirectly, into the Schrödinger equation. Among the more notable attempts in this direction have been those of Bohm and Bub (1966), Bialynicki-Birula and Mycielski (1976), Zurek (1981, 1989), Ghirardi *et al.* (1986), Weinberg (1987), Petrosky and Prigogine (1994), and Penrose (1994). Some of these attempts have been tested experimentally and their predicted effects have not been found. Others make predictions that are too sensitive for current instruments to detect so their validity is still an open question. Many do not predict new experimental results that could be checked and are simply meant to offer a justification for the existence of two distinct processes.

Of all these attempts, there are two which I refer to later. The first is the intriguing suggestion of Roger Penrose (1994). It has experimental consequences, but currently they are just outside the possibility of verification. He suggests using the nonlinear aspects of general relativity and that the collapse of the wavefunction will occur when gravitational effects are taken into account.

Consider a situation such as that of the Schrödinger cat paradox discussed previously. Rather than considering the cat as the endpoint of the experiment, we replace the cat by a billiard ball and suppose the triggering mechanism moves the ball from one position to another, with the possible positions of the center of the ball being separated by a small but macroscopic distance. As previously explained, when a single photon enters the apparatus the quantum analysis shows the ball will be in a linear superposition of the two separated states. According to general relativity, the space–time structure around the ball will depend on the position of the ball so there will be a linear superposition of space–time after the photon enters the box. Since general relativity is a nonlinear theory, Penrose (1994) argues that it is not possible to maintain this linear superposition of space–times when they are sufficiently different and the effect of the nonlinearity will be to bring about a collapse into one or the other of the two possible space–times.

Since these two different space–times are unstable, Penrose (1994) suggests that the greater the difference in the space–time structure, the quicker will be the decay into one or the other of the states. He then adds a heuristic energy argument to arrive at an expression for the reduction time. In effect, the greater the mass, the shorter the time for collapse. For a single neutron, the decay time is more than 10 million years, which explains why it is relatively easy to produce interference effects with neutrons. On the other hand, a drop of water with a radius of 1 μm would decay in about $\frac{1}{20}$ of a second, making it very difficult to see interference. If this process is applied to a macroscopic body such as a billiard ball or even a flea, the collapse into a well-defined state will take place very rapidly so that we will never see such macroscopic objects in a linear superposition of quantum states. Clearly there are systems in which the linear superposition lasts for a few seconds, so it should be possible to test this proposal. Unfortunately, to date these proposals have not been tested.

The second approach is one that I have been involved with and is not aimed specifically at trying to solve the measurement problem. It is an attempt to provide direct description of the individual quantum process. In the current approaches one can only talk about the results of measurements and there is no possibility of describing what is happening in between these measurements. In other words, it has been possible to provide an epistemological interpretation of quantum mechanics at the expense of an ontological interpretation, which is generally regarded as impossible. This was the position adopted by Bohr, and his general arguments were strongly reinforced by von Neumann (1955), who claimed to have rigorously proved that it was not possible to provide such an interpretation in principle. Assuming that an actual description of a quantum process would require additional ("hidden") parameters of some kind, von Neumann (1955) wrote, "It should be noted that we need not go any further into the mechanism of the "hidden parameters," since we know that the established results of quantum mechanics can never be re-derived with their help" (p. 324). This conclusion is manifestly wrong since there exists a counterexample, known as the de Broglie–Bohm interpretation, which has now been examined in detail and shown to provide a consistent explanation of nonrelativistic quantum mechanics (Bohm and Hiley, 1993; Holland, 1993).

The Bohm Interpretation

I discuss a particular variation of the previously discussed interpretation which, although having features in common with the ideas of de Broglie, was ultimately developed in a different way by Bohm and myself (Bohm and Hiley, 1993). Like de Broglie, this interpretation assumes that each particle has a precise position and momentum even in the quantum domain, despite the fact that we cannot know what they are because we cannot measure them to arbitrary accuracy at any one time. Since the position is well-defined at all times, it is possible to determine an ensemble of trajectories which the particles could travel along. The wavefunction, $\psi(\boldsymbol{r}, t)$, which is still assumed to satisfy the Schrödinger equation, now has a different meaning to that given to it in the standard interpretation. It is no longer to be regarded as a function of state of the particle. Rather, it is the description of a new kind of field that acts on the particle through a new potential called the quantum potential.

To see how the quantum potential arises, first it should be noted that the wavefunction is a complex function so it can be written in the form $\psi(\boldsymbol{r}, t) = R(\boldsymbol{r}, t)\exp[iS(\boldsymbol{r}, t)/\hbar]$. Substituting this expression into the Schrödinger equation and separating out the real and imaginary parts of the resulting equation, the real part gives

$$\frac{\partial S}{\partial t} + \frac{(\nabla S)^2}{2m} + V + Q = 0. \qquad [7]$$

The imaginary part gives Eq. (10), which I will discuss later. Equation (7) becomes identical to a single-particle Hamilton–Jacobi equation provided $Q = 0$. This equation was well-known before the development of quantum mechanics and describes the evolution of a classical particle. It can also be put in a more familiar form:

$$\frac{d\boldsymbol{p}}{dt} = -\nabla[V + Q], \qquad [8]$$

so that when $Q = 0$, it becomes Newton's equation of motion for a classical particle.

Thus, in the quantum domain, where Q is nonzero and takes the form

$$Q = -\frac{\hbar^2}{2m}\frac{\nabla^2 R}{R}, \qquad [9]$$

we have an extra potential which produces the behavior of the particle that is different from that expected in the classical domain.

It is well-known that Newton's equation produces particle trajectories in the classical case as does the Hamilton–Jacobi equation. We can then argue that when Q is very small, but not zero, it is still possible to calculate trajectories from Eq. (8) and that these trajectories will hardly differ from the classical trajectories. As Q slowly increases, the trajectories will increasingly differ from the classical trajectories, but at no point will we be able to say "At this point we must give up the notion of a trajectory." Indeed, these quantum trajectories can be (and have been) calculated for many different situations, including the classic two-slit interference experiment (Bohm and Hiley, 1993).

Quantum mechanics uses probability and in the Bohm approach the connection with probability emerges from the imaginary part of the Schrödinger equation. This can be written in the form

$$\frac{\partial P}{\partial t} + \nabla \times \left(P\frac{\nabla S}{m}\right) = 0. \qquad [10]$$

Here, $P(\boldsymbol{r}, t)$ $[= R(\boldsymbol{r}, t)^2]$ is interpreted as the probability of the particle to be at a particular point, $\boldsymbol{r}$, at time t. The statistics then arises simply from the contingent initial positions of the particle.

The existence of this approach shows that it is no longer possible to argue that quantum mechanics implies that the world is genuinely and fundamentally indeterministic. A deterministic theory will produce exactly the same results provided the statistics arise in a particular way; that is, they arise from our inability to control the initial position and momentum of the particle with sufficient precision. This lack of control is exactly what accounts for the uncertainty principle.

The Properties Implied by the Quantum Potential

Because the quantum potential appears alongside the classical potential in Eq. (8), it looks as if an additional classical potential has simply been added to Newton's equation of motion. Thus, it appears that we have found a way to describe quantum phenomena in terms of classical concepts, and that we have surprisingly retained determinism. To achieve this, all we seem to have done is to rewrite the Schrödinger equation in a form that reveals a new potential. If we probe deeper, however, we find that this new potential is totally different from any classical potential that has been used to date. I try to summarize these differences and show how they imply a radically new way of viewing nature which begins to remove the sharp distinction between mind and matter and thus is central to the topic of this chapter.

The first point to note is that the potential is derived from the quantum field $\psi(\boldsymbol{r}, t)$ and it is in the properties of this field that the differences arise. One feature that is of particular importance is that, unlike potentials derived from classical fields, the quantum potential is independent of the amplitude of the quantum field or wave. This means that a wave of very small amplitude can produce a large effect on the particle. If we examine Eq. (9), we see that the force depends on the second derivative of the amplitude so that we can say it depends on the form of the wave profile and not its amplitude.

For example, recall that in radio transmission the audio signal modulates the profile of the high-frequency carrier wave. Here, the audio energy can be very small, but its form can be amplified to produce a large effect in the radio itself, with any extra energy coming from a battery or an external source. By analogy, I argue that the small energy in the quantum wave can be magnified by some unknown internal process so as to produce a large effect on the particle. The suggestion that follows from this analogy is that the quantum wave is carrying information about the environment to the particle. Thus, when a particle passes through one of the slits in a two-slit interference device, the wave contains information of the presence of the other slit, its size, and its distance away from the first slit (Phillipidis *et al.,* 1979). It is not information that we can make use of as humans. It is information for the particle, which responds to it by changing the form of its movement. Literally, the quantum field informs the process.

The example using the radio is somewhat artificial, being mechanical and created by human endeavor. Perhaps a better example that occurs naturally in nature is the function of DNA in living cells. DNA is said to contain a code which is expressed in the form of the molecule and this form can be considered as the information content for this code. The "meaning" of the code is expressed in terms of processes involving messenger RNA molecules which "read" the code and carry out various activities elsewhere in the cell. Thus, in the process of cell growth, it is only the form of the DNA molecule that counts. The energy to carry out the instructions transported by the RNA is supplied by the rest of the cell. Moreover, at any moment only part of the DNA molecule is being read and giving rise to activity. The rest is passive, being only potentially active, and may become active according to the total situation in which the cell finds itself. Other parts of the DNA seem to be inactive and are regarded as redundant remains of the evolutionary history of the species.

This biological example indicates that we must distinguish three types of information: active, passive, and inactive. The active information is actually producing change. The passive information has the potential to become active in the right situation, whereas the inactive information is unlikely to become active again. It is remarkable that with these three distinctions we can provide a consistent account for all nonrelativistic quantum processes without producing the paradoxes in the standard approach. I will not discuss these here, but I refer the reader to Bohm and Hiley (1993).

In this approach there is no measurement problem since measurement is merely another physical process that produces results which have significance for us as observers. Thus, there is no necessity for a collapse of the wavefunction. In this approach the wavefunction is not a "substance" carrying significant amounts of energy. It is carrying information, and during the measurement some of the information is active while other aspects become inactive since they no longer contribute to the quantum potential acting on the particle. It is information becoming inactive that renders the collapse of the wavefunction unnecessary.

In this approach measurement is no longer passive in the sense that it merely reveals the properties that the system actually possesses. Rather, measurement is active and one must think of the whole measurement process as undergoing an active transformation in which the particle and the apparatus "fuse" before becoming separated again after a sufficient period of time. The fusion is described through the new quantum potential which arises as a result of the interaction between the measuring apparatus and the system under observation, and it is this quantum potential that links the system with the apparatus in an irreducible way. In this sense, measurement must be considered "participatory." Thus, a general picture emerges in which matter participates in matter giving rise to radically new types of behavior.

One of the fascinating features of the Bohm model is that although it was thought to be impossible by Bohr, it actually gives insights into some of the arguments that Bohr used in his approach to quantum mechanics. Bohr emphasized the impossibility of making a sharp separation between the observing apparatus and the observed system. He argued that they were to be regarded as forming an indivisible whole. In the Bohm approach, it is the quantum potential that provides the link between the two, and Bohr's only mistake was to insist that further analysis was not possible. Analysis is possible provided the role of the quantum potential is recognized. In other words, although the quantum potential allows analysis, it confirms the notion of indivisibility of the total process. To more clearly illustrate this point, it is necessary to consider the two-body system from the Bohm point of view.

Nonlocality in Quantum Mechanics

Before considering the details of the two-body system, I present some of the background to the intense debate that followed the publication of the paper by Einstein *et al.* (1935). They pointed out that in a two-particle system in which the particles had originally been coupled and then allowed to separate, the predictions of quantum mechanics seemed to indicate that the formalism was, in some sense, incomplete. The formalism implied that the distant particle was being affected by measurements made on the first particle even though there was no apparent force between them. To emphasize this point, Schrödinger (1936) wrote,

> In an earlier paper, EPR dealt with the following fact. If for a system which consists of two entirely separated systems the representative (or wavefunction) is known, then the current interpretation of quantum mechanics obliges us to admit not only that by suit-

> able measurements, taken on one of the two parts only, the state (or representative or wavefunction) of the other part can be determined without interfering with it, but also that, in spite of this noninterference, the state arrived at depends quite decidedly on what measurements one *chooses* to take — not only on the results they yield.

This measurement-dependent feature seemed to imply that some kind of action-at-a-distance was acting between the particles. The suggestion that some form of nonlocal action was involved was anathema to Einstein. He thought physics should be about a local reality unfolding in space–time in either a causal or stochastic way and it was for this reason that he argued that the quantum formalism was not complete and that some extra features were needed to describe the evolution of the quantum system. It was only much later that Einstein (1971) wrote, "I cannot seriously believe in it [QM] because the theory cannot be reconciled with the idea that physics should represent a reality in time and in space, free from spooky actions at a distance." Even Dirac (1973) was disturbed by this idea of nonlocality. He wrote,

> For an assembly of particles we can set up field quantities which do change in a local way, but when we interpret them in terms of the probabilities of particles, we get again something which is nonlocal. . . . That is rather like an action-at-a-distance theory. It is against the spirit of relativity, but it is the best we can do at the present time.

It seems that Dirac was thinking that if experiments were performed when these nonlocal effects were present then quantum mechanics may give the wrong results. Since these comments were made, many experiments have been performed and they all show that quantum mechanics produces the correct result in every case. For a discussion of some later experiments see Greenberger *et al.* (1990).

Although these results leave many physicists disturbed, Bohr (1935) accommodated them comfortably into his outlook. He wrote in his immediate reply to the EPR paper,

> 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 a system." Of course there is 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 define the possible types of predictions regarding the future behaviour of the system.

The word influence used in the last sentence is very curious. Bohr emphasizes that it is not a mechanical force; however, if it is not a mechanical force then what is it? How does the setting of one piece of measuring apparatus influence both outcomes? It was not until I examined the Bohm interpretation in more detail that I began to see that the possibility of an explanation of the word influence lay in the quantum potential. It was argued in the previous section that the quantum potential is not a mechanical effect; rather, it is an effect produced by information and that could clearly be regarded as an influence.

The mathematics that lies behind this effect involves two-particle wavefunctions that are said to be *entangled,* which simply means that the state cannot be written as a simple product of two one-particle states. The following is a typical example of a two-particle entangled state:

$$\Psi(\boldsymbol{r}_1, \boldsymbol{r}_2, t) = \frac{1}{\sqrt{2}}[\psi(\boldsymbol{r}_1, t)\phi(\boldsymbol{r}_2, t) - \phi(\boldsymbol{r}_1, t)\psi(\boldsymbol{r}_2, t)]. \quad [11]$$

Notice that for this wavefunction, the states of the individual particles are not well-defined. In the first term on the right-hand side, particle 1 is in the state ψ, whereas particle 2 is in state ϕ. In the second term, these states are interchanged! The act of measurement on any one of the two particles will produce one of the following two pairs of states: $\psi(\boldsymbol{r}_1, t)\phi(\boldsymbol{r}_2, t)$ or $\phi(\boldsymbol{r}_1, t)\psi(\boldsymbol{r}_2, t)$.

Thus, the states of the individual particles have become well-defined. This, of course, is just an example of the collapse of the wavefunction, but notice that the states of both systems have become well-defined after a measurement on only one of the particles. I emphasize that we could allow both systems to move very far apart so that there is no possible classical force connecting them before a measuring instrument is placed at the expected position of one of them. The result of the measurement on only one of the particles then determines the state of the other system immediately, even though the other system may be many miles away! [The longest distance that this has been tested for directly is 23 m (Paramanda and Butt, 1987), although a result of more than 4 km was reported (Ekert *et al.,* 1992)].

In presenting this analysis I have made implicit assumptions. I have assumed an interpretation in which the wavefunction is taken to provide the most complete description of the state of the system. This is often called the standard interpretation, but there are other interpretations which regard the wavefunction as playing a different role, and for these approaches nonlocality presents no difficulty. For example, in the Bohr interpretation the wavefunction is regarded as being part of an algorithm from which probabilities can be calculated and as such has no ontological significance. Such an approach has nothing to say about whether or not these effects are nonlocal.

The consistent histories interpretation has been developed in a way that avoids, or even regards as meaningless, questions concerning nonlocality (Omnés, 1994). These alternative approaches are possible essentially because they exploit the ambiguous relation between the individual and the wavefunction, but I do not believe that nonlocality can ultimately be avoided.

I now relate the Bohm interpretation to these questions. The importance of this approach to this question lies in the fact that it is possible to talk about the precise positions of the particles at all times. Thus, the notion of when an effect is nonlocal can be brought out in a very clear way.

To show how this comes about, we will first consider the two-body Schrödinger equation and substitute into it a general two-body wavefunction which can be written in the following form:

$$\psi(\boldsymbol{r}_1, \boldsymbol{r}_2, t) = R(\boldsymbol{r}_1, \boldsymbol{r}_2, t)\exp[iS(\boldsymbol{r}_1, \boldsymbol{r}_2, t)].$$

We then obtain the following equation:

$$\frac{\partial S}{\partial t} + \frac{(\nabla_1 S)^2}{2m} + \frac{(\nabla_2 S)^2}{2m} + V(\boldsymbol{r}_1, \boldsymbol{r}_2, t) + Q(\boldsymbol{r}_1, \boldsymbol{r}_2, t) = 0, \qquad [12]$$

where the quantum potential now takes the form

$$Q(\boldsymbol{r}_1, \boldsymbol{r}_2, t) = -\frac{1}{2m}\frac{\nabla_1^2 R + \nabla_2^2 R}{R(\boldsymbol{r}_1, \boldsymbol{r}_2, t)}. \qquad [13]$$

In this way, it can be seen that there is a two-body Hamilton–Jacobi equation (Eq. 12) which again contains the quantum potential (Eq. 13) so that it is possible to talk about individual trajectories for each of the particles.

Suppose the two particles are separated in space and that there are no classical forces between them, i.e., $V(\boldsymbol{r}, \boldsymbol{r}_2, t) = 0$. When the wavefunction is entangled, no matter how far the particles are apart they are still coupled by a quantum potential. In fact, the trajectories are correlated in the sense that the trajectory of particle 1 depends on the position of particle 2 and vice versa at a given time *t*. Thus, the particles are in some sense "together yet apart," but the essential point is that they are nonseparable because they are linked by a common quantum potential.

To make them separable, the wavefunction must be written in a product form: $\psi_A(\boldsymbol{r}_1, t)\psi_B(\boldsymbol{r}_2, t)$. It is not difficult to show that if the classical potential can also be written as a product, the two particles become completely decoupled and behave as independent particles. Thus, only systems with product wavefunctions are separable. All other wavefunctions give nonseparable behavior.

Another feature to emerge is that the quantum potential does not necessarily fall off as the distance between the two particles increases, i.e.,

$$Q(\boldsymbol{r}_1, \boldsymbol{r}_2, t) \neq 0 \quad \text{as} \quad |\boldsymbol{r}_1 - \boldsymbol{r}_2| \to \infty. \qquad [14]$$

This implies that for systems in an entangled state, it may never be possible to regard the two subsystems as independent even if we separate them by an infinite distance. Reductionism assumes that the world consists of independent entities that can be put together in interaction, but the most general wavefunctions used in quantum mechanics do not allow us to separate systems. Since quantum mechanics underlies all of physics, this seems to imply that we must abandon theories that are based on reductionism in our attempts to understand nature. It is this feature that I regard as the key element in understanding the nature of physical processes and, in particular, the mind–matter relationship (discussed later).

These nonlocal effects have been brought out most clearly in the Bohm model, but it could be argued that these effects arise only in this specific model and may not be true of other models. After reading about the Bohm model, Bell (1987) was able to show quite generally that all models in which particles were attributed specific properties and could reproduce quantum mechanics must necessarily be nonlocal. He showed that if a theory was to be a local theory then a certain inequality constructed out of pairs of correlation functions must be satisfied. The correlations calculated from quantum mechanics do not satisfy this inequality and experiments chosen specifically to test quantum mechanics in this area show the quantum mechanical calculations to be correct and, furthermore, have been shown to directly violate the Bell inequality. Therefore, any explanation that attributes well-defined properties to the particles must involve nonlocality.

I now discuss some of the consequences of this nonlocality. It should be noted that it is not possible for us to use this nonlocality to transfer information faster than the speed of light, so there is no direct conflict with relativity (Bohm and Hiley, 1993). The nonlocal potential organizes the particles to behave in a correlated way. If we extend these arguments to many body systems, we find that groups of particles belonging to the same entangled state act as if they form a whole, exhibiting a coordinated movement in which each particle reacts to the movement of all the others in a way that does not depend only on the classical forces between them. Furthermore, suppose there are two separate groups of particles occupying the same region of space–time, each group being coordinated by an entangled wavefunction. If particles from the different groups do not interact then the particles from one group do not see the coordinating quantum potential of the other group. In this sense, the quantum potential is a "private" potential shared only by members of the group.

This is very different from what we would expect from a physical theory used in the classical domain. Instead of giving rise to a mechanical model, the properties of the quantum field suggest that its main role is to organize groups of molecules into coordinated movement which is shaped by the environment in which the molecules find themselves. Such a behavior is exactly what is seen in superconductivity and superfluidity. It is the appearance of this nonlocality that suggests that a mechanical interpretation of such movements is not adequate. In a sense, the manifestation of nonlocality should not be a surprise since Bohr has already argued that quantum phenomena exhibit a kind of wholeness in which sharp separation is not possible. This kind of behavior is not present in classical systems. In the Bohm model, Bohr's notion of wholeness is reflected in the nonlocal properties of the quantum potential.

If all these points are taken together, the structure that begins to emerge is very reminiscent of the proposals of Whitehead (1929). He suggested that matter should be regarded as organic rather than mechanistic. The word organic is being used in the sense of systems being organized into a coherent whole in a way that cannot be explained by the mechanical interaction of the parts. In other words, the behavior of the whole system is more than a mere sum of its parts.

To further support this organic view, it should be recalled that the particles themselves ultimately emerge as structures in a more fundamental field. In this context, there is no basic immutable "rock-like" substance out of which all macroscopic matter emerges. There are no primary unchanging entities from which our world emerges. Ultimately, all is process or all is flux and the classical world is built up out of quasi-stable elements of this underlying process.

Thus, a new picture emerges in which the old mechanistic categories based on reductionism are no longer adequate and we should not force mathematical discoveries into the old mechanistic categories. What is called for is an exploration of new categories that are more in harmony with the way nature is rather than the way we would like it to be.

These new categories will have to accommodate both mechanical and organic aspects of nature as two sides of the same basic process. The study of biological systems has often indicated that a broader set of categories are needed but these have often been rejected in the hope that molecular physics would provide the necessary explanations. However, molecular physics is governed by quantum mechanics and here we see the need of a change that is reminiscent of the changes suggested by biology. Throughout my discussions with David Bohm, it seemed as if the differences between physics and biology were being eroded, and that quantum mechanical processes were becoming "mind-like," supporting Dyson's (1979) previous statement.

Since, as argued previously, particles and fields can be better understood if we regard them as being influenced by information, the new categories that we must explore should be sensitive to the kind of changes that are needed to accommodate both matter and mind without having to resort to Cartesian dualism. In embarking on such an undertaking, it will be necessary to go beyond quantum mechanics and to explore more radical approaches that will ultimately enable us to deal with both mind and matter in one theory.

Toward the Removal of the Cut between Mind and Matter

Before discussing more general ideas, I consider the specific suggestion of Beck and Eccles (1992) of a possible link between mind and matter using quantum mechanics. They argued from a dualist standpoint that mind can influence specific physical processes occurring in the brain by changing appropriate transition probability amplitudes. Their proposals left open the question as to how this change could be brought about other than by "willpower."

I propose that within the Bohm model, the connection between mind and matter arises through the mediation of the quantum potential. The idea is that the activity in thought modifies the quantum potential experienced by certain critical processes such as the onset of exocytosis described by Beck and Eccles. The modification of this potential by thought becomes more plausible once we accept that the quantum field carries information. In this case, it is not simply information about a passive environment for the quasi-particles involved in exocytosis but rather it is information that has been influenced by thought. This could still imply a dualist solution but I suggest that if mind and matter could be regarded as different aspects of a more general underlying process there would be no need for dualism. I will discuss this possibility later.

Another link between mind and matter has been made by Penrose (1990, 1994). As a result of his experiences as a mathematician, he suggests that processes occurring in the brain, such as the kind of intuition required to prove theorems, led him to the conclusion that such processes cannot be reproduced by any computational algorithm and therefore cannot be mimicked by a computer. Such processes are called noncomputable. Indeed, Penrose (1994) claimed to have proved that these processes must necessarily be noncomputable. His argument is long and technical and is still being challenged; it would be inappropriate to discuss it here, but for the purposes of my discussion I will assume that his conjecture is correct.

The next step in Penrose's (1994) argument is to identify possible sources of the noncomputability that could have relevance to the functioning of the brain. For this, he reconsiders the collapse of the wavefunction which he thinks is a real problem and which can be solved using gravity. Drawing on the work of Geroch and Hartle (1986), who showed in a very technical paper (the details of which are not relevant here) that the topological equivalence problem of four-dimensional spaces is noncomputable. From these results, Penrose argues that the collapse induced by gravity will be noncomputable, and it is this feature of the collapse process that provides the link between mind and matter.

The problem is to explore possible processes in the brain that will enable this link to be explored further. Penrose and Hammeroff (1996) proposed that the cytoskeleton must play a central role, and they have been exploring the possibility that microtubules might be involved in quantum computing. These are very exciting suggestions for further theoretical and experimental investigation. While the technical questions concerning the functioning of the microtubules are of interest in themselves, there are more general questions to be addressed. For example, will the noncomputable aspects of the collapse be rich enough to account for the type of intuitional processes that Penrose has in mind? I believe that the approach does not go deep enough and something more radical along the lines of a critical reappraisal of our basic categories is needed before such questions can be adequately addressed.

New Concepts

To begin this discussion it is important to realize that the general reticence of the physics community to become part of the matter–brain–mind debate lies in a deep-rooted and implicit belief in the Cartesian paradigm. Classical physics is concerned solely with matter, *res extensia,* whereas thought, *res cogitans,* has no place in physics. Matter is defined as existing in space in the form of separated and extended objects interacting through fields and forces. It is further assumed that matter is rational, obeying the immutable laws of physics. Newtonian physics assumes various local interactions between these objects which govern their movement, which is continuous and deterministic. For convenience, I call the categories necessary to carry out this program "Cartesian categories."

Mind, on the other hand, does not exist in space. Therefore, it does not have any notion of locality. Furthermore, it can appear to be irrational, jumping easily from one idea to another. It certainly does not appear to be deterministic, although it can become mechanical, going through routines that have been programmed at some earlier stage. There is also a kind of coherent "wholeness" that appears to lie behind understanding.

I now consider quantum mechanics from the standard viewpoint. At the particle level it appears indeterministic. There are "quantum jumps" which cannot be accounted for in terms of a continuous process in space–time, and there is a kind of nonseparablity or wholeness. It is further assumed that it is impossible to analyze the behavior of a particle in a way that is independent of the means of observation. However, if we pay attention only to the wavefunction, then everything is local because all the wavefunctions are local. Continuity and determinism also hold at this level since the wavefunction follows a well-defined differential equation, namely, the Schrödinger equation. In other words, we have successfully embedded quantum mechanics into the Cartesian categories at the level of the wavefunction but not at the level of the individual particle or field. Thus, we have a theory that provides an objective description independent of any observer. It was only the collapse problem that spoiled this theory and it is this problem that has caused much the debate.

von Neumann, Wigner, and others were forced to introduce the observer to complete the picture, but even this was done within the Cartesian paradigm with the mind of the observer intervening minimally at the last possible moment. Nevertheless, as I have previously remarked, this whole approach generates an uneasy feeling within the physics community and its members would like the mind to be excluded, in principle, from the discussion. However, all the current attempts to complete quantum mechanics within the Cartesian order and without introducing mind have been far from successful.

Partly motivated by this failure, both Bohm (1980) and Stapp (1993) have been moving tentatively toward a new approach which will bring mind and matter together. Bohm's ideas were bold, proposing a new order that he calls the implicate order (described later). Stapp's ideas emerge from Heisenberg's suggestions that the wavefunction represents all the potential outcomes of some deeper underlying process. These potentialities evolve in a deterministic manner following the Schrödinger equation. Then, at some stage there is a process of actualization that induces a transition from the "possible" to the "actual," with the actual process invariably making itself manifest by a registration in a macroscopic measuring device. The following quote will clarify Heisenberg's (1958a) position:

> If we want to describe what happens in an atomic event we have to realize that the word "happens" . . . applies to the physical not the psychical act of observation, and we may say that the transition from the "possible" to the "actual" takes place as soon as the interaction between the [atomic] object and the measuring device, and thereby with the rest of the world, has come into play; it is not connected with the act of registration of the result in the mind of the observer. The discontinuous change in the probability function, however, takes place with the act of registration, because it is the discontinuous change in our knowledge in the instant of registration that has its image in the discontinuous change in the probability function.

In this view, the wavefunction has a different meaning from the one used in the standard interpretation. Heisenberg

(1958b) summarized this as "a mathematics [that] represents no longer the behaviour of the elementary particles but rather our knowledge of this behaviour." Thus, Heisenberg does not regard the wavefunction as describing the state of a system, but, like Bohr, he regarded it as part of an algorithm which enables one to determine future possibilities. Since we cannot obtain complete knowledge of the system because only the properties of a complementary set can be defined precisely at any one instant, the wavefunction somehow represents our knowledge of the system at any given time. Since we do not have and cannot have complete knowledge of the system, we can only predict future possibilities. The wavefunction then represents the potentiality for future development.

The following is a natural question to ask: "Future potentialities of what?" Surely there is something or some process that is the source of the actual occurrences. Stapp does not specify the nature of this source but asserts that it is neither particle-like nor field-like. The evolution equations, although in a form that resembles the classical equation of motion that govern macroscopic matter, no longer represent the evolution of anything substantive. Rather, the "primal stuff" represented by the wavefunction has an "idea-like" character rather than being matter-like. Stapp (1993) noted,

> Indeed, quantum theory provides a detailed and explicit example of how an idea like primal stuff can be controlled in part by mathematical rules based in space–time. The actual events in quantum theory are likewise idea-like: Each such happening is a *choice* that selects as the "actual," in a way not controlled by any known or purported mechanical law, one of the potentialities generated by the quantum-mechanical law of evolution. (p. 221)

The Bohm's more general approach has its origins in his early attempts to understand the Bohr approach to quantum mechanics. In Bohm's book (1951), in which he tries to present Bohr's position, he draws attention to the analogies between thought processes and quantum phenomena. For example, he argues that there is something like an uncertainty principle operating in thought in the sense that thinking about one aspect of a thought process rules out the possibility of thinking about another aspect. There is an indivisibility in the sense that the thinker and the thought are in fact a product of thought itself and therefore cannot be separated except in some approximate limit. He even goes as far as to speculate that there may be key areas in the brain that are so sensitive and delicately balanced that they must be described in an essentially quantum-mechanical way even though the bulk of the brain may act like a general system of communications.

These ideas are further developed in the Bohm quantum potential model in which information plays a key role in organizing the behavior of groups of particles and fields. As discussed previously, the particles and fields are not to be regarded as some immutable lump of substance but rather as some quasi-stable, semiautonomous feature of a deeper underlying process. In the nonrelativistic theory the process the actualization is not necessary in the Bohm model since the quasi-stable particle can be regarded as actually stable in this domain. It is when we move into the relativistic domain that a process of actualization may be necessary even in the Bohm model.

The common feature in the proposals of both Bohm and Stapp are that in quantum processes, the sharp cut between matter and mind must be removed and consequently the Cartesian view that there is a sharp separation between *res extensia* and *res cogitans* should be abandoned. If the disjunction between mind and matter is removed, then it becomes possible to look at mind, thought, and consciousness in an entirely new way.

Psychophysical Implications: A New Order

In order to motivate the approach involving new categories, I return to the Bohm model. Here, our starting point was to give an account of individual quantum phenomena by regarding the wavefunction as an expression for a real field acting on a point-like particle. At first one's natural inclination is to regard the field and the particles as separate features, whereas they are actually different aspects of the same entity, namely, the quantum particle.

Regarding the two-body problem, it is surprising that nonlocality is present. I suggest that this nonlocality arises because the two particles have been regarded as two separate entities linked by the quantum potential, but this linkage cannot be thought of as a mechanical linkage because it is provided by the quantum field which is not separate from the particle. Something more subtle is involved. Indeed, the fact that the entangled particles seem to have properties that go beyond a mere sum of the individual properties and that this entangled state requires a quantum potential that is not a preassigned function of the positions of the particles raises the question as to whether they are, in actuality, two separate particles.

Could it be that a "particle" is simply an outward manifestation of some deeper underlying process, like the ripples on the surface of water? Initially, it seems that particles formed in this way would be too ephemeral and would seem to offer no possibility of explaining the stability of the macroscopic world, but it should be remembered that most of the elementary particles are extremely ephemeral. It is only when they form composites such as the proton–electron system in hydrogen that we find the necessary stability, provided, of course, that the temperature is low enough and

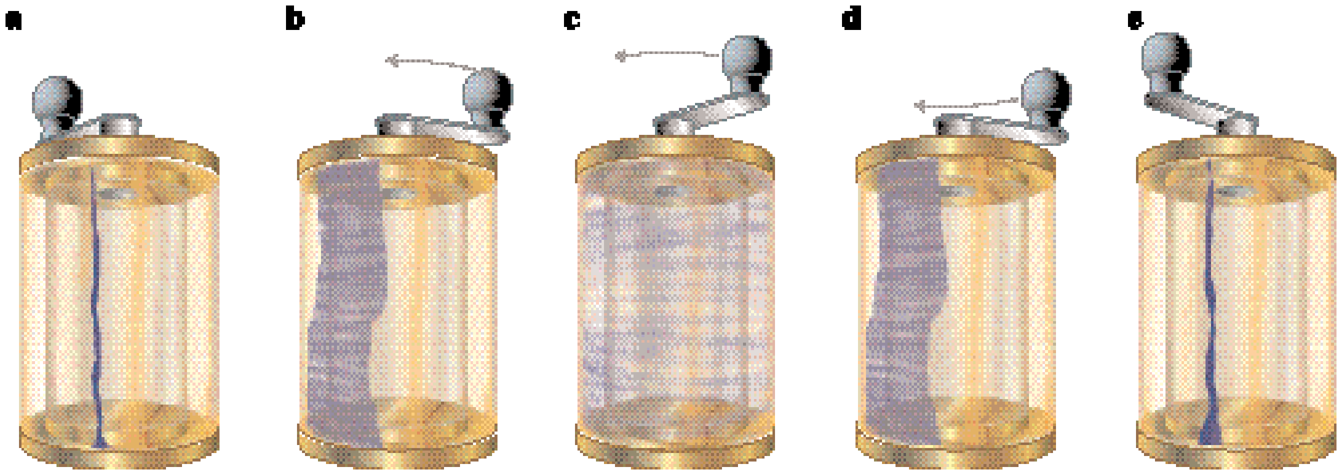

FIGURE 2 The unmixing experiment used to illustrate the notion of an implicate order. Implicate order is shown by an apparatus consisting of two transparent plastic cylinders. The space between the two cylinders is filled with glycerine, a transparent viscous liquid. Into this space a ribbon of dye is injected (a) which represents the initial ordered alignment of the particles. The outer cylinder remains fixed, whereas the inner cylinder is rotated (b) until the dye appears to be completely mixed with the glycerine (c), giving the impression of the disappearance of the initial alignment. By changing the direction of rotation (d) the particles realign and the original ordered ribbon reappears (e) (reproduced with permission from Brewer and Hahn, 1985).

there is no antihydrogen present. In the presence of antihydrogen, hydrogen is also ephemeral, reducing ultimately to electromagnetic energy.

We now consider particles as an outer manifestation of some total process of activity. How do we think about such a possibility? To illustrate what he had in mind, Bohm used the analogy of what I call the "unmixing" experiment (Bohm, 1980). Consider two concentric transparent cylinders that can rotate relative to each other. Between these cylinders there is some glycerine (Fig. 2). If a spot of dye is placed in the glycerine and the inner cylinder rotated, the spot of dye becomes smeared out and eventually disappears. There is nothing surprising about this, but it is surprising that if the rotation is reversed, then the spot of dye reappears. This actually works in practice and is easily explained in terms of the laminar flow of the glycerine under slow rotation. What I want to illustrate here is that in the "mixed" state, there does not seem to be any distinctive order present. However, the order is implicit in the liquid and our activity of unwinding makes manifest what is implicitly present within the glycerine.

Furthermore, we can arrange to insert a series of spots of dye in the glycerine. Place one spot at x_1, and then rotate the inner cylinder n_1 times. Then place another spot at x_2 and rotate the inner cylinder n_2 times and so on repeating a total of N times. If we were then to unwind the cylinder, we would see a series of spots unfolding and then reenfolding. If the spots were very close together we would have the impression of the movement of some kind of "object" starting from position x_1 and finishing at position x_N (Fig. 3). However, no object has actually moved anywhere. There is simply a creation of distinguished forms that are made manifest by the process of unfolding. Therefore, what we have taken to be the continuous movement of substance is actually a continuous unfoldment of form. If this were a correct view of what we now call an elementary particle then we could begin to understand why, when a particle encounters a pair of slits, its motion can be conditioned by a pair of slits. The slits act as an obstruction to the unfolding process, thus generating the motion that gives rise to the interference pattern.

This model may also be able to provide a better understanding of nonlocality. If the pair of particles are a simultaneous manifestation of the same underlying process, then they are clearly not two separate objects. They are inseparable, not because they are locked together by some force but because they are two aspects of the same total process. Clearly, if we measure a property of one of the "particles," we must necessarily disrupt the total process giving form to the pair.

In order to be able to discuss these ideas, Bohm (1980) introduced the term *implicate order* to describe processes of this nature; that is, the order that will eventually manifest is implicit in the underlying process itself. What can be made manifest is termed the *explicit order* so that nature appears as an unfolding process of manifestation and remanifestation. It is interesting to note that these very general ideas can be put into mathematical form and the resulting mathematics is similar to that used in quantum mechanics (Frescura and Hiley, 1980a,b).

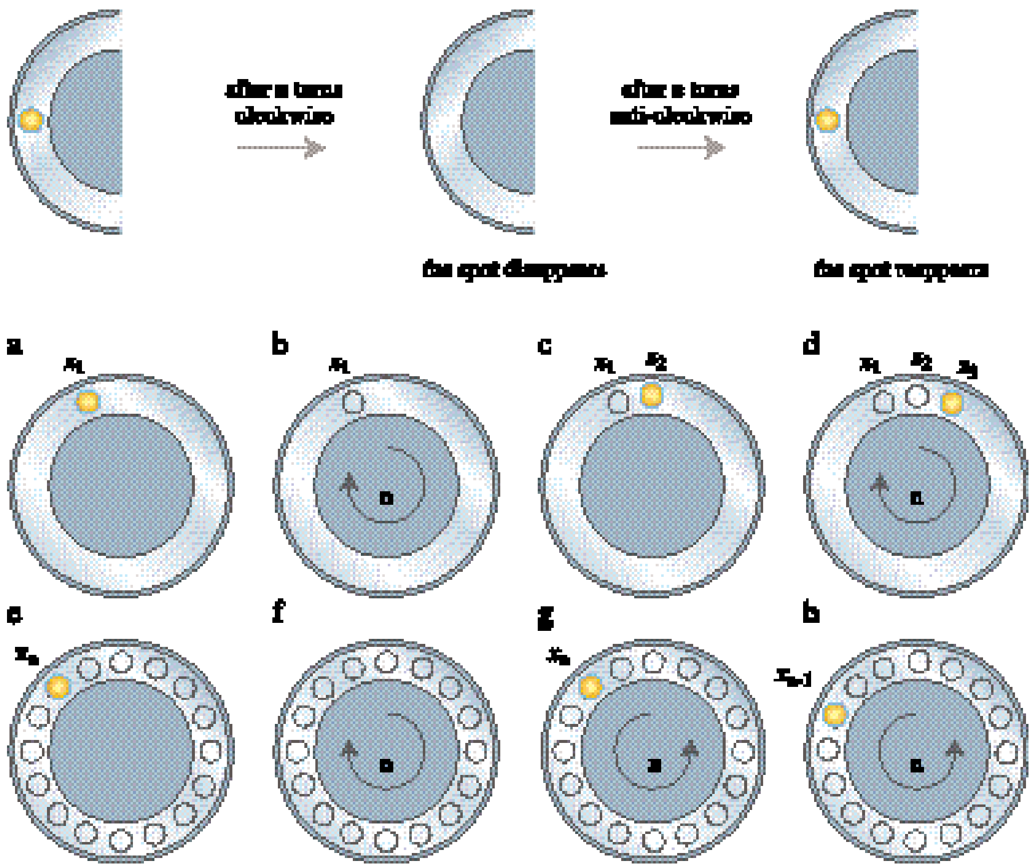

FIGURE 3 The disappearing spots. Is a quantum particle the continuation of substance or of form? (Top) The phenomenon described in Fig. 2 is summarized, imagining the double cylinder viewed from above. (Bottom) A variation of this experiment is shown in which several ribbons of dye are injected into the glycerine in sequence. The first ribbon is placed at position x_1 (a) and the cylinder is then rotated n turns until the dye disappears (b). A second ribbon is then placed at position x_2 (c) and the cylinder is again rotated n turns (d) and so on, repeating the operation several times (e and f). If one then begins to turn the cylinder in the opposite direction (g), from above we would see a series of spots which appear and then disappear (h), giving the impression of some type of object which moves from position x_N to x_1.

An important new general feature that emerges from these considerations is the possibility that not everything can be made explicit at any given time. This feature is already implied in the glycerine experiment. In the case of the series of spots, only one spot at a time can be made manifest. In order to make manifest another spot, the first manifest spot must be enfolded back into the glycerine and so on.

Thus, there exists the possibility of a whole series of noncompatible explicate orders, none being more primary than any other. This is to be contrasted with the Cartesian order in which it is assumed that the whole of nature can be laid out in a unique space–time for our intellectual examination. Everything in the material world can be reduced to one level. Nothing more complicated is required. This is why it was such a shock when it was first realized that quantum mechanics requires a principle of complimentarity. Here, we are asked to view complementarity as arising from uncertainty principle operating within the Cartesian framework. However, it is not merely an uncertainty; it is a new ontological principle that arises from the fact that it is not possible to construct a piece of physical apparatus that will allow one to display complementary properties together. Within the Cartesian order, complimentarity seems totally mysterious. There exists no structural reason as to why these incompatibilities exist. Within the notion of the implicate order, a structural reason emerges and provides a new way of searching for explanations.

The New Order and Mind

As previously remarked, the descriptive forms that we use are similar to those used when we describe thought. For example, thought is about the organization of form and structure. It is certainly not about material substance. [It is interesting to note that mathematics is an articulation of form and structure and so is also about thought. I have shown elsewhere that by pursuing these ideas, we are again led to mathematics that is central to quantum mechanics (Hiley, 1996).] We lift thought into immediate attention and hold these thoughts as quasi-stable structures which we can reflect on, forming a display in the "Cartesian theater (Dennett, 1991). However, we know how too easily a particular thought pattern disappears into the background, but in thought this lack of stability is not conceived as a problem.

Furthermore, to organize any thought process, we need information. We need to give form to our thought and we do this using information stored in memories. According to Lashley (1942), this storage is not located in some "pigeon hole" in the brain. Rather, it seems to be stored in a dynamic form. Memories are then re-created through activity in the brain. Thus, we need active information to develop new and meaningful structures of thought. Much of the information that is available to us is not relevant except in particular circumstances. Therefore, much of our information is passive. We are always forgetting bits of information as well as being unaware of much more. In other words, there is plenty of inactive information in the world of thought. Therefore, at a very general level, our proposals for the interpretation of quantum mechanics seem to be suggesting that there may not be such a great difference between matter and thought as the dualist has led us to believe. It is this feature that Stapp (1993) also emphasizes in his approach.

When I am talking in this way I am very much aware that the word information as it is used in everyday life has a much more restrictive meaning. It is a noun and as such seems to play a passive role and is used to point to "items of knowledge," lifeless forms such as a list of facts and figures. However, as mentioned previously, the notion of information that I am referring to is information that gives meaning to a particular activity, and it is the active side of the notion of information that seems to be relevant both for material process and for thought.

I now consider the wider aspects of the new worldview provided by the implicate order. Within this view, we can ask whether anything more can be said about the mind–body relationship. To answer this question, I begin by highlighting a particular feature that is implicit in my argument and actually is quite close to Bohr's point of view. Bohr insisted that our immediate experience of quantum phenomena was through the macroscopic world which is described by classical physics. We call this world the *manifest* world. Here, the word manifest is used in its literal sense, namely, "what can beheld in the hand," or more generally, what can be held in the hand, eye, and ultimately in our measuring instruments. Everything in this classical world is constituted of very stable structures that are outside of each other and that interact only through local mechanical interactions.

Quantum phenomena, with their interference effects, nonlocality, and other puzzling features, belong to a world that is subtle. Again, the word subtle literally means "rarefied, highly refined, delicate, indefinable." It is clear that quantum phenomena cannot be "held in the hand" because, as previously mentioned, measurement produces an uncontrollable and unpredictable change in what we are trying to measure. Each element participates irreducibly in all others. The absence of externality and separability makes this world very illusive to grasp in our physical instruments. It is a world that sustains itself intimately with the underlying implicate order. The classical world is a world that needs only a single, unique explicate order.

In this view, all processes have two sides — a manifest side and a subtle side. The subtle side is organized through active information and displayed in the manifest side. In the case of quantum processes, the active information is mediated by the quantum potential. When we use quantum field theory, there is the possibility of more than one level of organization so that our theories become hierarchical and cannot be reduced to one level. This means that we have room to discuss various degrees of subtlety, each being revealed in its own relatively manifest level. Again, in physics there are relationships between the levels organized in terms of either the quantum potential or a more general potential called the superquantum potential and, of course, there are the additional possibility of a third level and so on.

We can now ask if there is anything like this occurring in the mind–body relationship. Bohm (1990) argues that there is and gives the following example. Suppose someone who is out walking on a dark night suddenly becomes aware of a movement in the shadows. Immediately there is an upsurge of involuntary and essentially unconscious activity; adrenaline flows, the heartbeat increases, and neurochemicals of various kinds are released to produce physical movements. As more perceptual information is received and the shadow is seen to be a friend, all the chemical activity ceases. If the perception is one of danger, the activity increases. Here, it is the active information that is organizing chemical and other physical processes in the brain and indeed in the whole body.

To what extent is this activity similar to what occurs at the quantum level? Clearly there are similarities, but at the same time there seems to be one important difference, namely, that in our subjective experience action can be mediated by reflection in conscious thought. We can suspend physical activity and think the problem through before acting. In contrast, in the case of the electron, the action of the information is immediate. There does not seem to be any possibility of any form of conscious activity.

However, on further reflection it can be seen that the difference is not as great as it might appear to be initially. In the case of thought, this reflection involves the suspension of physical action to allow the process of thought to continue. However, the suspension of physical activity is immediate on perceiving the need to do this. This perception acts at a higher level in the human thought process. These higher levels can only exist if a system is complex enough and structured in such a way as to function in this way. Thus, the difference is one of complexity, but the principle is the same so that the difference is not so great as we might expect. Processes involving mind are merely much more subtle. In this sense, the emergence of consciousness in our view is much closer to the ideas suggested by John Searle (1992).

It is proposed that in the brain, there is a manifest (or physical) side and a subtle (or mental) side acting at various levels. At each level, we can regard one side as the manifest or material side and the other as the subtle or mental side. The material side involves electrochemical processes of various kinds, neuron activity, and so on. The mental side involves the subtle or virtual activities that can be actualized by active information mediating between the two sides. Thus, it is the active information that provides the link between the two sides. In this context, we are providing a more appropriate setting for the proposals of Beck and Eccles (1992), but we are not resorting to dualism because these sides must not be thought of as actually distinct.

Recall the discussion of the quantum particle in which the field and the particle were different aspects of the same process. Thus, the manifest and the subtle sides are not to be thought of as two distinct and separate processes. They are two aspects of the same process. The logical distinction of the two sides necessitates a logical linkage. Since these distinctions are descriptive rather than actual, varying degrees of subtlety and manifestness are possible. This makes a hierarchy of levels possible so that what is subtle at one level can become what is manifest at the next level and so on. In other words, if we examine the mental side, this too can be divided into a relatively stable and manifest side and a yet more subtle side. Thus, there is no real division between what is manifest and what is subtle; consequently, there is no real division between mind and matter and between psyche and soma. In this sense, the subtle side involved in quantum phenomena can be regarded as having a primitive mind-like quality. There is no Cartesian dualism. There is a complete wholeness in which the mental and physical sides participate.

Acknowledgment

I thank Dr. Jane Nicklin for her helpful discussions.

References Cited

ALBERT, D., and LOEWER, B. (1988). *Synthese* **86,** 87–98.

BECK, F., and ECCLES, J. C. (1992). *Proc. Natl. Acad. Sci. USA* **89,** 11357–11361.

BELL, J. S. (1987). *Speakable and Unspeakable in Quantum Mechanics.* Cambridge Univ. Press, Cambridge, UK.

BIALYNICKI-BIRULA, I., and MYCIELSKI, J. (1976). *Ann. Phys.* (*New York*) **100,** 62–93.

BOHM, D. (1951). *Quantum Theory.* Prentice-Hall, Englewood Cliffs, NJ.

BOHM, D. (1980). *Wholeness and the Implicate Order.* Routledge, London.

BOHM, D. (1990). *Philos. Psychol.* **3,** 271–278.

BOHM, D., and BUB, J. (1966). *Rev. Modern Phys.* **38,** 435–469.

BOHM, D., and HILEY, B. J. (1993). *The Undivided Universe: An Ontological Interpretation of Quantum Mechanics.* Routledge, London.

BOHR, N. (1935). *Phys. Rev.* **48,** 696–702.

BOHR, N. (1961). *Atomic Physics and Human Knowledge.* Science Editions, New York.

BREWER, R. G., and HAHN, E. L. (1985). *Sci. Am.*

DENNETT, D. C. (1991). *Consciousness Explained.* Little, Brown, London.

DEWITT, B. S. (1971). In *Proceedings of the International School of Physics: Enrico Fermi: Foundations of Quantum Mechanics* (B. d'Espagnat, Ed.), pp. 211–261.

DIRAC, P. A. M. (1973). In *The Physicist's Conception of Nature* (J. Mehra, Ed.), p.10. Reidel, Dordrecht.

DYSON, F. (1979). *Disturbing the Universe.* Harper & Row, New York.

EINSTEIN, A. (1971). In *The Born–Einstein Letters (Correspondence between Albert Einstein and Max and Hedwig Born (1916–1955) with Commentaries by Max Born)* (I. Born, Ed.), p. 158. Macmillian, London.

EINSTEIN, A., PODOLSKY, P., and ROSEN, N. (1935). *Phys. Rev.* **47,** 777–780.

EKERT, A., RARITY, J. G., TAPSTER, P. R., and PALMA, G. M. (1992). *Phys. Rev. Lett.* **69,** 1293–1295.

EVERETT, H. (1973). In *The Many-Worlds Interpretation of Quantum Mechanics* (B. DeWitt and N. Graham, Eds.). Princeton Univ. Press, Princeton, NJ.

FRESCURA, F. A. M., and HILEY, B. J. (1980a). *Found. Phys.* **10,** 7–31.

FRESCURA, F. A. M., and HILEY, B. J. (1980b). *Found. Phys.* **10,** 705–722.

GELL-MANN, M. (1994). *The Jaguar and the Quark: Adventures in the Simple and Complex.* Little, Brown, London.

GELL-MANN, M., and HARTLE, J. B. (1989). In *Proceedings of the 3rd International Symposium on the Foundations of Quantum Mechanics* (S. Kobayashi, Ed.). Physical Society of Japan, Tokyo.

GEROCH, R., and Hartle, J. B. (1986). *Found. Phys.* **16,** 533.

GHIRARDI, G. C., RIMINI, A., and WEBER, T. (1986). *Phys. Rev.* **D34,** 470–491.

GREENBERGER, D. M., HORNE, M. A., SHIMONY, A., and ZEILINGER, A. (1990). *Am. J. Phys.* **58,** 1131–1143.

HAMMEROFF, S., and PENROSE, R. (1996). In *Towards a Science of Consciousness: Contributions from the 1994 Tucson Conference* (S. Hammeroff, A. Kasniak, and A. Scott, Eds.). MIT Press, Cambridge.

HEISENBERG, W. (1958a). *Physics and Philosophy,* p. 54. Harper & Rowe, New York.

HEISENBERG, W. (1958b). *Daedalus* **87,** 95–108.

HILEY, B. J. (1996). *Consciousness at the Crossroads of Cognitive Science and Philosophy.*

HOLLAND, P. (1993). *The Quantum Theory of Motion.* Cambridge Univ. Press, Cambridge, UK.

LASHLEY, K. S. (1942). In *Biological Symposia, VII, Visual Mechanisms,* pp. 301–322. Jaques Cattell Press, Lancaster, UK.

LOCKWOOD, M. (1989). *Mind, Brain and the Quantum.* Blackwell, Oxford.

OMNÉS, R. (1994). *The Interpretation of Quantum Mechanics.* Princeton Univ. Press, Princeton, NJ.

PARAMANDA, V., and BUTT, D. (1987). *J. Phys.* **13G,** 449–452.

PENROSE, R. (1990). *The Emperor's New Mind,* p. 565. Vintage, London.

PENROSE, R. (1994). *Shadows of the Mind.* Oxford Univ. Press, Oxford.

PETROSKY, T., and PRIGOGINE, I. (1994). *Chaos Solitons Fractals* **4,** 311–359.

PHILIPPIDIS, C., DEWDNEY, C., and HILEY, B. J. (1979). *Nuovo Cimento,* 52B.

SCHRÖDINGER, E. (1935). *Naturwissensch.* **23,** 807–812, 823–828, 844–849. [Translated by J. D. Trimmer, *Proc. Am. Philos. Soc.,* 323–338, 1980]

SCHRÖDINGER, E. (1936). *Proc. Cambridge Philos. Soc.* **32,** 446–452.

SEARLE, J. R. (1992). *The Rediscovery of the Mind.* MIT Press, Cambridge.

STAPP, H. P. (1993). *Mind, Matter and Quantum Mechanics.* Springer, Berlin.

VON NEUMANN, J. (1955). *Mathematical Foundations of Quantum Mechanics.* Princeton Univ. Press, Princeton, NJ.

WHEELER, J. A. (1957). *Rev. Modern Phys.* **29,** 463–465.

WHITEHEAD, A. N. (1929). *Process and Reality.* Cambridge Univ. Press, Cambridge, UK.

WIGNER, E. P. (1986). In *The Scientist Speculates* (I. H. Good, Ed,). State University of New York Press, New York.

ZUREK, W. H. (1981). *Phys. Rev.* **24D,** 1516–1525.

ZUREK, W. H. (1989). *Nature* **341,** 119–124.