LBL-27862
UC-414

Lawrence Berkeley Laboratory

UNIVERSITY OF CALIFORNIA

Physics Division

Invited talk presented at the Patterns in the Universe: An International Symposium, Washington, DC, October 20–22, 1989, and to be published in the Proceedings

Quantum Theory and the Emergence of Patterns in the Universe

H.P. Stapp

November 1989

U. C. Lawrence Berkeley Laboratory
Library, Berkeley

FOR REFERENCE

Not to be taken from this room

LBL-27862
Copy 1
Bldg. 50 Library.

Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

November 10, 1989 LBL-27862

Quantum Theory and the Emergence of Patterns in the Universe*

Henry P. Stapp

Theoretical Physics Group
Physics Division
Lawrence Berkeley Laboratory
1 Cyclotron Road
Berkeley, California 94720

Invited talk at the Symposium
Patterns in the Universe: An International Symposium.
Smithsonian Institute, Washington D.C.
Oct. 20–22, 1989

*This work was supported by the Director, Office of Energy Research, Office of High Energy and Nuclear Physics, Division of High Energy Physics of the U.S. Department of Energy under Contract DE-AC03-76SF00098.

I. Introduction

The topic of this symposium is the quest to discover, define, and interpret patterns in the universe. This quest has two parts. To discover and define these patterns is the task of science: this part of the quest is producing a copious flow of reliable information. To interpret or give meaning to these patterns is the task of natural philosophy: this part has not kept pace.

The difficulty with the second part may stem from a failure to take seriously *all* the information provided by the first part. When contemplating the universe one usually thinks of it in the "common sense" way suggested by the ideas of classical physics. But modern science – quantum theory in particular – has shown that the universe must be fundamentally different from our common sense idea of it.

Quantum theory does not tell us what the world is actually like. It gives a mathematical description of certain patterns *in our observations*, without specifying what is actually going on between these observations. In this raw form, as a mere set of mathematical rules describing empirical patterns in human observations, quantum theory fails to be of much help to the natural philosopher. However, some scientists, either to satisfy their own curiosities, or in the hope of eventually enlarging the scope of science, have constructed pictures of what the world *could* be like: they have constructed conceptions of the universe that are at least *compatible* with the patterns in our observations described by quantum theory. The three simplest conceptions are Bohm's pilot–wave model,[1] Everett's many–worlds interpretation,[2] and Heisenberg's actual–events ontology.[3] Each of these is very different from the other two, and fundamentally different also from the classical picture of the universe.

These conceptions of nature have not yet entered in any very significant way into science itself. This is because they are concerned mainly with aspects of nature that we do *not* observe, and hence with distinctions that are difficult to test by empirical means. On the other hand, these conceptions of nature are an important part of the database of natural philosophy, which is precisely the endeavor see what conclusions can be drawn about the universe itself, and our place within it, on the basis of the information provided by science.

My aim here is to describe, within the framework of each of these three conceptions of nature, the emergence of patterns in the universe. The three conceptions give very different pictures of how particular patterns are selected, and how they come into being. I shall begin by introducing some elementary ideas from quantum theory, will then describe the main ideas of these three conceptions of nature, and will finally discuss the emergence of patterns in the universe.

2. Quantum Theory

Quantum theory is a statistical theory: it gives predictions about probabilities. A key quantity is the probability density $P(\vec{x}, t)$: this is the probability per unit volume that a particle will be found to lie in the vicinity of point $\vec{x}$ at time t. If the system being examined has two particles then the probability density is $P(\vec{x}_1, \vec{x}_2, t)$; if the system has n particles then the probability density is $P(\vec{x}_1, ..., \vec{x}_n, t)$.

A basic assertion of quantum theory is that there is , for an n–particle system, quantity $\psi(\vec{x}_1, \vec{x}_2, ..., \vec{x}_n, t)$ such that

$$P(\vec{x}_1, \vec{x}_2, ..., \vec{x}_n, t) = |\psi(\vec{x}_1, \vec{x}_2, ..., \vec{x}_n, t)|^2 . \tag{1}$$

This quantity $\psi(\vec{x}_1, ..., \vec{x}_n, t)$ is actually a *pair* of numbers, and the right–hand side of equation (1) represents the sum of the squares of these two numbers.

This quantity $\psi(\vec{x}_1, \vec{x}_2, ..., \vec{x}_n, t)$ plays a central role in quantum theory, and is called the "wave function". The word "wave" comes from the fact that each of the two numbers just mentioned executes, in general, an oscillatory behavior, as one changes either the time t, or any one of the positions $\vec{x}_1$, or $\vec{x}_2$, or $\vec{x}_3$, etc. Thus the form of $\psi(\vec{x}_1, \vec{x}_2, ..., \vec{x}_n, t)$ resembles a *wave* moving on the surface of a 3n–dimensional pond.

Quantum theory uses $\psi(\vec{x}_1, \vec{x}_2, ..., \vec{x}_n, t)$ simply to make predictions about the *results of observations* on the n–particle system: the theory maintains resolute silence about what is actually going on between our observations. The three conceptions of nature give three alternative possible pictures of what is going on. Each of these conceptions interprets the wave function $\psi(\vec{x}_1, ..., \vec{x}_n, t)$ of quantum theory in its own way.

3. The Pilot–Wave Model

In the pilot–wave model an n–particle system is considered to be composed of the wave function $\psi(\vec{x}_1, \vec{x}_2, ..., \vec{x}_n, t)$ and a trajectory function $x(t) \equiv (\vec{x}_1(t), \vec{x}_2(t), ..., \vec{x}_n(t))$. The symbol $\vec{x}_1(t)$ represents the trajectory of the first particle – it is simply an infinite set of numbers that specifies where the first particle will be at each instant of time. The symbol $\vec{x}_2(t)$ represents, similarly, the complete history of the motion of the second particle, etc. Thus the composite trajectory $x(t)$, being the collection of all the individual trajectories, gives the full history of the entire n–particle system.

These n particles move in accordance with a fixed law of motion, which, however, is not the one proposed by Newton. Instead, the trajectory $x(t)$ in the $3n$–dimensional space is directed always *perpendicularly* to the wave front of the wave function $\psi(\vec{x}_1, \vec{x}_2, ..., \vec{x}_n, t)$. Thus the wave function *guides*, or *pilots*, the motions of the n particles.

This model seems, at first, conceptually not much different from the model provided by classical physics: only the law of motion is changed. However, two peculiar features of the model should be appreciated.

The first peculiar feature is that the theory is highly nonlocal. If one introduces an external disturbance that shifts the location of just *one* particle, say the first one, then this shift in $\vec{x}_1(t)$ moves the trajectory $x(t) = (\vec{x}_1(t), \vec{x}_2(t), ..., \vec{x}_n(t))$ to a new point in the $3n$–dimensional space. At this new point the wave front in the $3n$–dimensional space has a new direction, in general. Consequently the motions of <u>all</u> n particles will immediately be changed. Thus a disturbance of any *one* of the particles of a system generally affects strongly the motions of *all* the particles, no matter how far apart they are.

This instantaneous action–at–a–distance is contrary to the ideas of the theory of relativity. However, in versions of the pilot–wave model built on relativistic quantum field theory all the *statistical predictions* of the relativistic theory will be maintained, even though the underlying individual–system dynamics is highly nonlocal.

This nonlocal feature of the pilot–wave model was the stimulant for the celebrated Bell's theorem, which showed, on general grounds, that any theory

of this general kind, even though it agrees with the no–action–at–a–distance requirements of the theory of relativity at the level of *statistical* predictions, must have, in principle, *very strong* nonlocal effects at the level of the underlying individual–system dynamics. Thus the universe must be, in any ontology of this kind, essentially a single nonlocal nonseparable entity.

The second peculiar feature of the pilot–wave ontology arises in connection with measurements. In quantum theory there are certain measurable quantities which, if measured, will be found to lie at *one* of several distinct possible values. A pointer on a devices that measures this quantity will typically move to *one* of a set of distinct possible locations, say location 1, or 2, or 3. Each distinct location of the pointer corresponds one of the distinct possible values of the measured quantity.

The process of measurement plays a crucial role in quantum theory, and it is important, both in the present context and for what follows, to understand how the wave function of the system consisting of the measured system *and* the measuring device behaves during this process of measurement. A typical picture of what happens is shown in Fig. 1

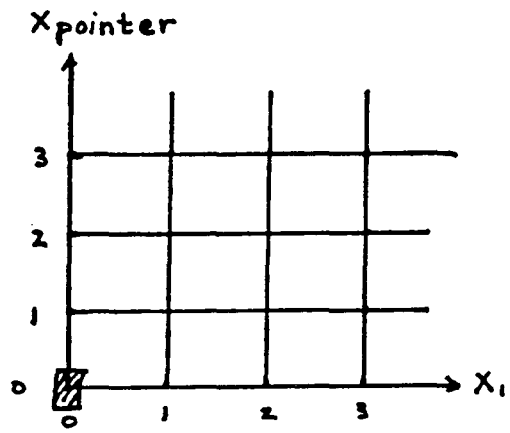

Figure 1a. The horizontal axis represents the variable x_1 being measured. The vertical axis represents the location of, say, the tip of the pointer of the measuring device. The shaded patch represents the region where the probability function, or wave function, is nonzero. Initially the pointer is resting near zero. The initial value of x_1 happens, in this example, also to be near zero.

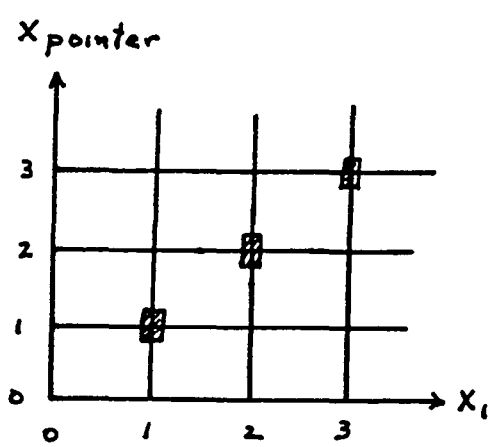

Figure 1b. Just after the interaction between the measuring device and the quantum object the region where the probability function is nonzero has separated into three patches. In the first patch the pointer is near 1, and the variable x_1 is near 1; in the second patch the pointer is near 2 and the variable x_1 is near 2; etc. Thus the position of the pointer becomes *correlated* to the value of the quantity x_1 that is being measured.

Just after the measurement the pointer has a certain probability to be near position 1, a certain probability to be near position 2, and a certain probability to be near position 3. The probability for it to be not near to any one of these three locations is either zero or virtually zero. Also, the measurement process has forced the value of x_1, which was formerly near zero, to become confined to one of three (in this example) well separated narrow regions.

In the course of time the pointer may return to its original resting point, zero. But before that happens the pointer will almost certainly interact with gas molecules or photons or other quanta. The effect of these interactions is to ensure that, if one considers *all* of the relevant variables, then the continuations into the future of the three separate patches in Fig. 1b will remain separated from each other for all of eternity, or at least, in general, for billions of years: for all practical purposes the separated patches will remain forever separated.

The trajectory function $x(t)$ is represented by a single point in Fig. 1a, and by a single point in Fig. 1b. If this point lies in the single patch in Fig. 1a, then it must, by virtue of the equation of motion for $x(t)$, move into *one* of the three separated patches in Fig. 1b. Moreover, it will remain in this particular separated patch for all of eternity. The other patches are called "empty patches".

The equation of motion for $x(t)$, although nonlocal in the 3–dimensional sense, is local in the 3n–dimensional sense: the motion depends on the values of ψ only in the immediate neighborhood of the point $x(t)$ itself. This means that those separated patches into which the point $x(t)$ does *not* move (i.e. the empty patches) can never influence the motion of $x(t)$.

This arrangement is not a very economical way for nature to operate: the "empty patches" continue to exist and evolve objectively for all of eternity, even though they can never have any influence on the motion of any particle.

In the pilot–wave ontology it is assumed that human experience is tied directly only to the motions of the *particles*: experience is assumed to be not tied directly to the wave function ψ, even though ψ is considered to be objectively real. This assumption allows each physical point, such as the tip of the pointer on our measuring device, to appear in a definite location, even though the places where the associated wave function ψ is nonzero can be, as in our example, not

confined to any single small region. However, this assumption also means that in this ontology the "empty patches", although they will continue to exist objectively and evolve for all of eternity, can never influence any human experience. This is not very economical.

4. The Many–Worlds Interpretation

The many–worlds interpretation resolves the awkward problem just mentioned by deleting from the ontology the trajectory function $x(t)$: the universe is represented by the wave function alone. This is more economical. The nonlocal aspect is also eliminated by this change, for the nonlocal aspect was precisely the nonlocal character of the equation of motion for the trajectory function $x(t)$.

In the measurement situation described above there are generally several patches in which the wave function is nonzero: there is one such patch corresponding to each of the possible locations N of the pointer. The many–worlds interpretation of this situation is that *each* of the corresponding results N *actually occurs.*

This interpretation must be squared with the fact that what we observe, in any actual situation, is just *one* of the alternative possible results, not all of them.

The reconciliation is achieved by considering the part of the wave function corresponding to the brains of the human observers. When a community of observers observes the location of the pointer then the wave function must, by virtue of the quantum mechanical law of motion, evolve in a way such that the patch in which the pointer lies in position N will come to contain a *corresponding* set of brain wave functions. This set contains one brain wave function for each member of the community of observers. The memory structures associated with each of the individual brain wave functions of this set will correspond to the associated observer's having seen the pointer lying *exclusively at the single position* N. The situation is indicated in Fig. 2

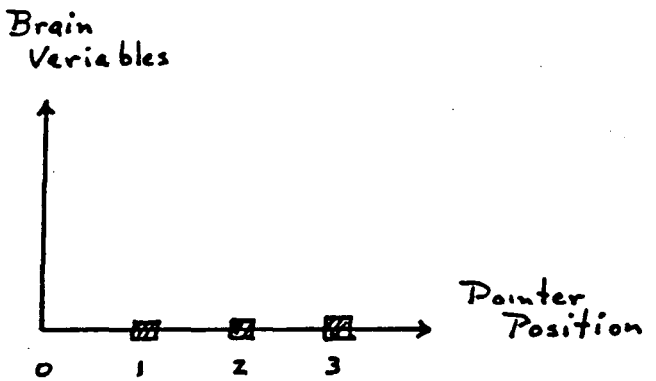

Figure 2a. The horizontal axis represents the location of the pointer, with the three patches representing the three locations 1, 2, and 3. The vertical axis represents the brain variables. Before the observation by human observers the wave function represents a state in which the brains of the observers are not correlated to the position of the pointer.

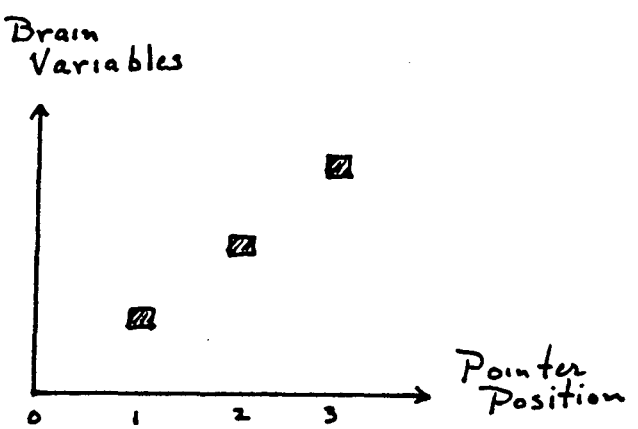

Figure 2b. After the observation of the position of the pointer by the human observers the structures of their brains become correlated to the position of the pointer. Thus the three patches in Fig. 2a become shifted in different ways in the dimensions that represent the variables that describe the brains of the observers.

The equation of motion of the quantum mechanical wave function guarantees that this should happen: no special assumption is needed, beyond the

natural assumption that structures corresponding to what we observe become imbedded in some way in the structures of our brains. The quantum mechanical equations ensure, moreover, that the patch of the wave function representing the community of observers who observed the pointer to be at position N will evolve in exactly the same way that it would evolve if the patches representing the *other* communities of observers did not exist. Thus each such community must be unaware of the existence of the others: its evolution is completely unaffected by the existence or nonexistence of the patches corresponding to the other values of the position of the pointer. Appearances are thereby saved, and they are saved *automatically* by the laws of quantum mechanics, *without any special assumptions.* This is the great virtue of this interpretation.

There is, however, a difficulty. The patches corresponding to the different pointer locations N will generally have different "weights": the different patches will correspond, in accordance to formula (1), to different probabilities. For example, the probability corresponding to pointer location 1 might be $\sqrt{2}$ larger than the probability corresponding to pointer location 2. But if both of these two possible results actually occur, then what does it mean to say that the "probability" of one result is $\sqrt{2}$ larger than that of the other?

Intuitively, it means that just before the measurement is performed I can say that the probability that after the measurement is performed I shall find myself to have observed result 1 is $\sqrt{2}$ larger than the probability that I shall find myself to have observed result 2. By doing many repeats of the experiment I can make similar statements corresponding to probabilities that are very nearly zero or one. However, this does not fundamentally alter the situation.

The only way to make really clear[4] the idea that the probability that I shall observe result 1 is $\sqrt{2}$ larger than the probability that I shall observe result 2, if both results actually occur, is either to say that there is an infinite number of psychological "I's" present before the measurement, and that these will divide themselves among the two possibilities in the ratio of $\sqrt{2}$ to 1, or that *each* psychological "I" present before the measurement will branch into an infinite set of "I's" after the measurement, and that this infinite set will divide itself in the ratio of $\sqrt{2}$ to 1.

This apparent necessity of introducing infinite sets of psychological "I's" destroys the ontological simplicity of the original many–worlds interpretation, in which there was only *one* ontological element, the single wave function of the world. It also brings in a host of related problems such as the question of the relationships of the infinity of "I's" to the evolving wave function of the world, and to the infinities of evolving "I's" of other persons.

These problems with the infinite sets of "I's" seem to arise from the fact that in the many–worlds ontology one has taken the wave function, which is mathematically structured so as to represent to the *probabilities* for various possible things to happen, and mistakenly identified it with the actual world itself. Then there is no natural thing for the probabilities to refer to.

5. The Actual–Events Ontology

In the actual–events ontology the wave function represents not the actual world itself, but rather the "potential", or "tendencies", or "propensities" for actual events to occur. Each actual event is represented by a "quantum jump" of the (Heisenberg) state of the universe.

In the measurement situation discussed above it is postulated that a quantum jump will occur. This actual event selects one of the alternative possible macroscopically distinct pointer locations: *one* of the patches discussed above will be actualized, and all others will be eliminated.

The "propensities" for each of the various alternative possibilities to occur are fixed by the "weights", or probabilities, associated via equation (1) with the corresponding patches of the wave function of the universe. This interpretation brings the significance of the wave function directly into line with its role in the quantum formalism, i.e., as a representation of the *probabilities* for actual things to occur, rather than as a representation of the actual things themselves.

There is still, within this general framework, a tremendous amount of freedom in regard to the precise details of the quantum jumps. Consequently, the Heisenberg ontology represents a large class of similar ontologies, not just one single precisely defined ontology.

The actual event is represented by a change in the Heisenberg state vector. This change is the change induced by a projection operator that "projects" the

state onto one of the patches mentioned above. This projection changes the wave function $\psi(\vec{x}_1, \vec{x}_2, ...\vec{x}_n, t)$ over *all* of $3n$–space and time. That is, the quantum jump induces a change

$$\psi_N(\vec{x}_1, \vec{x}_2, ..., \vec{x}_n, t) \rightarrow \psi_{N+1}(\vec{x}_1, \vec{x}_2, ..., \vec{x}_n, t),$$

where on both sides of this equation the variable t ranges over all times. This "time" variable t is "mathematical time": it is connected with the mathematically prescribed evolution of the *propensities.* The *actual* changes are the (stochastic) quantum jumps. These are numbered by the index N. This variable N can be called the *actual* time, or the *process* time: it specifies the stage in the actual evolution of the universe.

I have, in this brief account, imagined the universe to consist of some fixed number n of particles: actually the full "wave function" depends on the sets of positions $(\vec{x}_1, ..., \vec{x}_n)$ for all the different possible numbers n of particles in the universe.

6. The Emergence of Structure

Having thus described the main features of the three simplest quantum ontologies I can turn to the consideration, within each of these three conceptions of nature, of the emergence of patterns in the universe.

The outstanding feature of the observed universe, when viewed from a general quantum mechanical perspective, is its extreme particularness. Each fiber in every leaf on every tree lies in some particular place. Every word in every book is some particular word, not a blurred superposition of many possible words. What fixes all of these particular things to be exactly what they are, and not something else?

In the pilot–wave model the answer to this question is the same as it was in classical physics: "the initial conditions". We have become accustomed to this idea, but it is really completely astounding. Somehow, at the birth of the universe, all of the particularness of the entire history of the universe becomes precisely fixed, all at once, and from nothing at all. In this single stupendous event the entire creative impulse of universe is completely expended; thereafter there is nothing but a pre–ordained mechanical evolution.

This view of creation is the vision of classical mechanics, and it carries over directly to the pilot–wave model.

The pilot–wave ontology is manifestly incomplete: an outside agent is required to fix the initial conditions. Given these conditions, the structure of the universe then unfolds like clockwork, and reveals, in due course, the richness of particular patterns that was implicit in the initial settings. A tiny shift of these initial settings would have led, almost surely, to a tremendous change in all of the particulars that we see about us.

There is one big difference between the classical ontology and the pilot–wave ontology: in the pilot–wave ontology, in contrast to the classical picture, there is an intricate nonlocal interlocking of the spatially separated parts of the universe. This connection washes out on the statistical level, and is consequently concealed from the casual observer.

The many–worlds ontology is, in many ways, the reverse of the pilot–wave picture. In the many–worlds ontology there could be, initially, virtually no form or particularness at all. In this ontology the law of evolution does not simply propagate the pre–existing particularness: rather it *itself* generates superpositions of alternative particular possible patterns, each of which is now considered to be an actuality. Thus the particularness is *created* in the process of the continual branchings of the possibilities: it is an emergent property; it need not be present initially.

The distinctness and particularness of the patterns we observe are, in the many–worlds ontology, not generally features of the physical world itself: they are features of our perceptions of the world. The distinctness and particularness of observed patterns arise, strictly speaking, from the cohesiveness and individualness of the perceiving human being. This is because the quantum mechanical law of evolution does not generally produce sharply separated distinct possibilities: it normally produces only smooth superpositions of possibilities, that are, moreover, defined only relative to each other. Thus the emergence of the particularness and distinctness of the patterns we observe is, in the many–worlds ontology, a consequence of a cohesiveness and individualness that must, as a special extra assumption, be imposed by this ontology on the human psyche.

The actual–events ontology combines features of the other two. As in the many–worlds ontology, the initial conditions can be bland and formless. Hence there is no need for an outside agent of prodigious power. The particularness of the universe can come in, not all at once at the beginning, but gradually, and always in the context of the already existing situation. On the other hand, in the actual–events ontology the distinctness and particularness of patterns in the universe is not a subjective quality, arising from a special assumption of the individualness of the human psyche. The distinctness and particularness of these patterns arise, rather, directly from the fundamental postulated distinctness and particularness of the actual events that comprise them. Likewise, the distinctness and particularness of the human psyche arises from the distinctness and particularness of the actual events that comprise it.

These psychological events can be equated in a natural way to actual events in the physical world.[5] Actual events are non–predetermined selections. By virtue of this identification of experienced events with certain kinds of actual events human beings become, via these selections, active participants in the emergence of patterns in the universe. They are not, as in the pilot–wave ontology, merely witnesses to patterns implicit already in the initial conditions of the universe. Nor are they, as in the many–worlds ontology, merely observers, from every possible distinct human perspective, of a universe that is essentially a continuous superposition of every possibility.

These quantum conceptions of the emergence of patterns in the universe are so profoundly different from the conception that arises from the classical picture of nature, and so far richer in their potentialities, that it is surely irrational and irresponsible to try to give meaning to the patterns in the universe while locked in the framework of a classical conception that is rigorously incompatible with these patterns themselves.

References

1. D. Bohm, A suggested interpretation of quantum theory in terms of "hidden" variables, Physical Review **85**, 166 (1952); D. Bohm and B.J. Hiley, An ontological basis for the quantum theory, Physics Reports **144**, 1881.

2. Hugh Everett III, "Relative state" formulation of quantum mechanics, Reviews of Modern Physics **29**, 454 (1957).

3. W. Heisenberg, Physics and Philosophy, Harper and Row, New York, 1958 Ch III; H.P. Stapp, Quantum ontologies, in Bell's Theorem, Quantum Theory, and Conceptions of the Universe, ed. M. Kafatos, and also LBL–26181, 1988.

4. David Z. Albert and Barry Loewer, Interpretation of the many–worlds interpretation, Synthese **77**, 195 (1988). Sidney Putnam, private communication.

5. Henry P. Stapp, Quantum theory of consciousness, Lawrence Berkeley Laboratory Report LBL–27543, 1989.

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
TECHNICAL INFORMATION DEPARTMENT
BERKELEY, CALIFORNIA 94720