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Two No-Collapse Interpretations of Quantum Theory

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> It is the problem he had had (Schrödinger 1935a) with his cat. He thought that it could not be both dead and alive. But the wavefunction showed no such commitment, superposing the possibilities. Either the wavefunction, as given by the Schrödinger equation, is not everything or is not right.'' Bell, ''Are there Quantum Jumps'' p.2

A short list of conventional wisdom concerning the philosophy of quantum theory would include:
i) There is a division between the quantum world and the macroscopic world with each conforming to its own set of laws. An isolated quantum system evolves in accordance with linear laws until it is measured. At that point the linear laws are suspended and the system's state *collapses* to an eigenstate of the observable measured.
ii) Quantum theory is incompatible with a Laplacian universe. There are in nature objective non-epistemic probabilities.
iii) A quantum system does not simultaneously possess precise values for all genuine physical quantities and no hidden variable theory which assigns such values is possible.
iv) Quantum mechanics is not locally causal.
v) A realist interpretation of quantum theory is ruled out by the preceding members of the list.

The entries on the list are vague and oversimplified, as conventional wisdom often is. But it is useful to have the list before us

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since we will be describing two ways of interpretating quantum theory which are decidedly unconventional. The first interpretation was originally suggested by DeBroglie, extensively developed by Bohm, and refined by Bell.[1] We call it the BB view. The second is a version of Everett's many world interpretation which we have developed and call "the many minds view" (the MM view).[2] Both interpretations reject the division of reality, are Laplacian, and are unabashedly realist. Both take the first of Bell's (above) alternatives, holding that Shrödinger's equation is right but not everything. To interpret quantum theory each adds new (although different) ontology and laws governing that ontology. We will not argue that either interpretation is *the* correct one, although we will give some reasons to think that either is preferable to the interpretations which underlie the conventional wisdom. Since the two interpretations are, we think, of great philosophical interest and since they are unknown to most philosophers, even philosophers of physics, we will here be content to describe them.

BACKGROUND

The standard formulation of elementary (non-relativistic) quantum theory includes the following principles:[3]

1. For any quantum system S there is a Hilbert Space H such that the physical state $\$$ of S is represented by a vector $\$$ in H and every normalized vector in H represents a physically possible state.
2. As long as S remains isolated its state $\$(t)$ evolves in accordance with a linear equation e.g. Schrödinger's equation.

The empirical import of the theory is provided by an association of physical quantities Q (called "observables") e.g. position and momentum, with Hermetian operators O and rules connecting states and observables with measurements. The rules are:

3. If the state of S is represented by $\$$ and observable Q is represented by O and $O|\$(t)> = q|\$(t)$ ($\$$ is an eigenvector of O with eigenvalue q) then the value of Q is q.

An ideal measurement of Q on S is an interaction between a measuring device M and S such that if S is in an eigenstate of Q with value q then M will definitely register this value and a second immediately following measurement will register the same value.

4. If $\$$ is not an eigenstate of O but $\$ = c_1 A_1 + \dots$ where the A_i are a complete basis of eigenvectors of O then the probability of a measurement of Q yielding q_k is c_k^2.

Finally, there is a rule, called "the Projection Postulate," connecting the result of an ideal measurement on S with its state immediately after the treatment.

> 5. Immediately after an ideal measurement of O which yields $O = q_k$ the state of S is A_k. A measurement may thus bring about about a "collapse" of a superposition into an eigenstate of the observable measured.

Applications of the theory employ a vast amount of information concerning how to represent states and observables by vectors and operators, how to prepare systems in particular states, how to measure observables etc. Such applications have been enormously successful in predicting and systematizing the results of experiment and observation. Quantum theory accounts for the stability of matter, molecular structure, particle-radiation interactions and so on. It is now taken to be the fundamental physical theory in that any theory concerning forces, particles, fields, strings, etc. is is expected to conform to it.

It has been known for a long time that the quantum theory possesses certain perplexing, even bizarre, features. One is that for any observable, e.g. position, there are other "incompatible" observables, e.g. momentum, such that if S is in an eigenstate of one it is not in an eigenstate of the other. This means that states of the theory do not *assign* precise values to all observables. It also means that it is physically impossible to build a device which simultaneously measures incompatible observables.

A second perplexing feature involves the existence of non-separable states. An example is the EPRB state

EPRB $1/\sqrt{2}\ (|\uparrow>_1|\downarrow>_2\ -\ |\downarrow>_1\ |\uparrow>_2)$

In this state the spins (in any direction) of electrons 1 and 2 are anti-correlated (their sum is 0) although EPRB does not assign any definite spin to either electron separately (and is inconsistent with quantum states which assign definite spins.) When a component, say in the x direction, of spin of one of the electrons is measured, the state of the whole system collapses (in accordance with the generalization of 5 to systems with more than one degree of freedom) into eigenstates of the spin component measured. This instantaneous change of state struck Einstein as being "spooky action at a distance."[4] He thought that it could be avoided by supposing that the EPRB state is not the complete physical state and that there are "hidden variables" which determine the measurement results. But John Bell showed that this (and similar) suppositions can reproduce the quantum mechanical predictions only by invoking the action at a distance Einstein wanted to avoid.[5] It is widely thought that this and related results show that nature itself is nonlocal.[6]

Perhaps the most puzzling feature of quantum theory concerns the role of measurement. The theory specifies two ways in which systems evolve. In accordance with Schrödinger's law when isolated and in accordance with the projection postulate when measured. But the theory doesn't tell us which interactions are measurements and which are not. And that is a problem since 2 and 5 describe incompatible processes. Let Q be an observable of S with two eigenstates A_1 and A_2 with eigenvalues, a_1 and a_2, and M be a measuring device with three distinct states, R, B_1 and B_2 (corresponding say to a pointer occupying three distinct positions). Suppose also that when S is in A_i and M in R at the beginning of the measurement then at its conclusion S will still be in A_i and M will be in B_i (for $i = 1,2$). Finally, suppose that the pre-measurement state of S is $c_1|A_1> + c_2|A_2>$. Then, if the measurement processes conforms to 2 the post-measurement state $S + M$ will be

$$\text{CAT} \quad c_1 \mid A_1 > \mid B_1 > + c_2 \mid A_2 > B_2 > .$$

CAT is a non-separable state which assigns no value to Q or to the position of the pointer. It is a state similar to the one in Schrödinger's famous thought experiment in which a cat (which plays the role of a measuring device) is neither alive nor dead but is in a superposition of such states. It seems impossible for this to be the complete state of the cat. We may be able to live with, if not understand, superpositions of spin properties but we are likely to feel sure that the cat must be either dead or alive. On the other hand, if the measurement is described by 5 then the post measurement state of $S + M$ will be either $|A_1 > |B_1 >$ or $|A_2 > |B_2 >$. These are states in which the cat is either alive or dead. So 5 seems to be the more reasonable description of measurement. But other interactions which produce correlations between the states of systems, for example, the interaction which produces the EPRB state, are known to satisfy 2, not 5. Furthermore, quantum theory entails that there are empirical differences between either $|A_1 > |B_1 >$ and $|A_2 > |B_2 >$ and CAT.[8] The problem of saying exactly where the division between processes satisfying 2 and those satisfying 5 lies and justifying the selection has come to be known as "The Measurement Problem" and is the most important problem faced by any interpretation of the theory.

There is a standard "interpretation" which usually goes along with standard quantum theory and which is supposed to provide a way of talking about the theory and its puzzles.[9] The "conventional wisdom" at the beginning of this paper is mostly based on this way of thinking. According to the standard interpretation the quantum state of a quantum system is its complete physical state. This means, for example, that an electron in an eigenstate of momentum is not in an eigenstate of position and so has no definite position. According to the standard interpretation position properties, e.g. located at q, are not applicable to such an electron and statements like "the particle is located at q" are not merely false but meaningless. On this account an electron is a very strange "particle" since its state evolving in accordance with 2 does not assign it (and so it fails to possess) a definite trajectory. On the other hand, if the position of such an electron is measured the result will certainly be a particular position and the post-measurement state of the electron will be (according to 5) an eigenstate of position. On the standard interpretation "measurement" is an active processes, both making a property applicable to a system and yielding a value for the property. Obviously, measurement cannot, as it is in classical physics, always be understood as revealing a pre-existing value.

The standard interpretation says that measuring the x-spin of one of the electrons of a pair in the EPRB state changes the state and so alters the observables which possess precise values. Prior to the measurement neither electron has a definite x-spin while afterwards both have definite and anti-correlated x-spins. According to Bohr the measurement influences "the very conditions which define the possible types of prediction regarding the future behavior of the system . . ."[10] Thus, in an EPRB state a measurement may not only create a result but create it at a distance. Bohr says that this non-local influence is "non-mechanical" and for this reason it is supposed to be unproblematic. Whatever it is, Einstein's term for it, "ghostly," is apt.

The standard interpretation responds to the measurement problem by insisting on a division between the quantum and the classical realms. It is sometimes said (e.g. by Bohr) that measuring devices must be described classically (i.e. not according to 1.) even to formulate quantum theory. Then the measuring device (the same for cats) being classical cannot be in a state like CAT. Other times, it is said that while the measuring device can be described quantum mechanically the measurement process satisfies 5 and so the final state of M has the pointer at a particular position. There are variations within the standard interpretation concerning exactly where the dividing line is to be drawn. This vagueness is sometimes excused by citing arguments which purport to show that from a practical point of view it doesn't matter much exactly where the line is drawn since experiments designed to test various alternatives are not feasable.

Einstein said of the standard interpretation that it is "a tranquilizing philosophy [. . .] a gentle pillow for the true believer from which he cannot easily be aroused."[11] From the point of view of explicitness and logical coherence it certainly leaves a lot to be desired. Its claim that the quantum state is complete, its reliance on a vague division between the quantum and the classical, and its postulation of the collapse give this interpretation a distinctly non-realist flavor. Many of its adherents tend to think of quantum theory not as a description of natural processes but merely as a calculational device for predicting the outcomes of experiments. It is especially difficult to think of the collapse as a real physical process. Exactly when in the measurement process does it take place? We have no idea of its physical details or why measurements should cause collapses of states or how it can operate at a distance. Measurement devices, whether they be photographic plates, or cats, or brains are, after all, composed of atoms. It is incredible that at some point of complexity law 2 should be suspended and law 5 take over.[11′]

If we want a realist and explicit interpretation of quantum theory it is natural to wonder whether the collapse can be eliminated. If all processes were governed by Schrödinger's equation there would be no need to divide the world into quantum and classical realms. But the suggestion that Schrödinger's equation describes all changes of state faces enormous difficulties. As we have emphasized, the Schrödinger evolution *determinstisically* leads to CAT, a state which assigns no definite value either to the pointer position or to A. Any account which says that (2) is the only dynamics will have to explain i) why experiments seem to have definite outcomes ii) why after measurement the state of S seems to evolve from an eigenstate of the observable measured and iii) why the probabilistic predicitions of 4 are correct. It is not easy to see how this can be done.

Since we will soon describe two "far out" attempts to do without 5 it will be useful to take a brief look at a conservative proposal for dismissing the measurement problem.[12] The proposal is based on a theorem to the effect that when M is a macroscopic object the state CAT of M + S cannot be distinguished from the mixture which assigns probability 1/2 to each of the states $| A_i >$ $| B_i >$ by measurements which are feasable.[13] Even if this claim is correct it fails to explain why our experiments produce, or seem to produce, definite outcomes, e.g. pointer to the left, since as Bell observes CAT makes no commitment to a definite outcome. One can see that something has gone wrong by trying to apply this argument to a measurement which includes a person P reading the pointer. Suppose that seeing (or believing) that the pointer is to the left (right) corresponds to macro-states C_1, C_2. Then according to the argument the state of $P + M + S$ at the conclusion of P looking at M is indistinguishable from the corresponding mixture. Now it may be that there is no practical experiment that P (or anyone else) can perform which will distinguish the two, but it will, of course, be obvious to P what the final state is since he will know what he believes. He will certainly be in a definite state of belief and that state is quite different from the superposition. Saving the appearances without the collapse will require something more radical than this.

THE BOHM-BELL VIEW

On the BB view a system of n particles is characterized by i) a wave function $\$ (x_1, \ldots x_n, t)$ and ii) functions $q(t) = <q_1(t) \ldots q_n(t)>$ which are interpreted as the locations of the particles at t. $\$ (x_1 \ldots, t)$ evolves in accordance with Schrodinger's equation while $q(t)$ evolves in accordance with

6. $dq/dt = f[\$(q(t),t),\ \$\ (q(t),t))]$

where f is $j(x,t)/|\$(t)|^2$ ($j(x,t)$ is the probability current $1/2\mathrm{Im}\$^*(x,t)$ $/dx\ \$(x,t)$). If the system consists of a single particle p located at x then 6 says that p moves along with the probability fluid at x. (That is, it moves toward regions of greater probability amplitude with a velocity proportional to the rate of change of amplitude.) To obtain the familiar quantum mechanical probabilities BB assumes that the initial probability density, $pd(q(t_o))$ is

7. $pd(q(t_0) = |\$(t_0,q(t_0)|^2.$

6 and 7 imply that for all t the probability density of $q(t)$ is $|\$(t,x)|^2$. The probability distribution at t_0 can be thought of as the result of a random selection of initial conditions which satisfies 7. Since the BB dynamics are completely deterministic after t_0 probability must be given an epistemic interpretation.[14]

The BB view embodies an ontological outlook we call "Positionism." According to Positionism a particle always possesses a definite position and its position is its only intrinsic property. The task of physics is to discover the fundamental laws which determine temporal evolution of the positions of particles. On the BB view these laws involve the quantum state which ultimately guides the motions of particles. An interaction between two systems of particles involves a redistribution of the positions of the particles where their final positions are determined by their initial positions and by the systems' quantum states. In a measurement the positions of the particles in a measuring device (say a pointer) are correlated with a feature of the measured systems. This is a world view that would have been familiar to Newton and Laplace.

It is possible to show that the BB view reproduces all the experimental predictions of standard quantum theory in so far as we consider these measurements as understood by Positionism; i.e. in resulting in the positions of pointers etc.[15] For example, the BB view, like the standard interpretation, entails that the probability that a position measurement will find the particle in some region R is $\int_R |\$(x,t)|^2 dx$. But unlike in the standard interpretation a position measurement can here always be thought of as revealing the particle's pre-existing position. Although the particle always has a perfectly definite position and a definite momentum 2, 6 and 7 conspire to make it impossible ever to make measurements which permit predictions which violate the uncertainty relations. Thus, the uncertainty relations emerge as epistemological constraints which are enforced by the dynamics of measuring processes.

The BB view needs to be complicated a bit to take account of internal degrees of freedom like spin. The wave function of a particle with spin (1/2 spin) looks like this: $c_1 \downarrow \$_1(x,t) > \; + \; c_2 \uparrow \$_2(x,t) >$ where ↑ is spin up in the z direction). Principle 6 now looks like this:

6* $$dq/dt = c_1 f(\$_1, \nabla \$) + c_2 f(\$_2, \nabla \$_2)$$

In this treatment spin is not an intrinsic feature of the particle but a property of the wave which guides the particle. A "measurement" of an electron's z-spin consists of passing it through a magnetic field oriented in the z direction. The electron must emerge on either the "up" or "down" path (indicating the value of its z-spin). In accord with Positionism the measurement consists in correlating spin with position. Let's look at such a "measurement" a bit more carefully. Suppose that the electron is initially in $1/\sqrt{2}\; |\$>(|\uparrow_z> + |\downarrow_z>)$. When the wave with its electron enters the field it splits into "up" and "down" components only one of which carries the electron. Whether the electron moves "up" or "down" depends on its initial position when it enters the field, on the geometry of the field, and on the wave. The process is all completely deterministic although impossible to predict since it is not possible to know enough about the particle's initial position and the wave. It follows from 6 that once the waves are separated spatially the electron's motion is determined only by the component that carries it; say the "up" component. A consequence of this is that if the electron travels through a second z-oriented magnetic field the equations of motion guarantee that the electron again moves on the "up" path. At least this is so as long as the waves remain spatially separated. Should the wave components come to overlap the "down" component may affect how the particle moves and a measurement might record a "down" result. But, if the electron's position as it emerges on the "up" path is recorded in the position of a macroscopic apparatus then it is enormously unlikely that the wave (which is now a non-separable wave correlating the position of the particle with the positions of billions of other particles) will ever overlap with the other wave component. Because of this the "unoccupied" wave component can be neglected. Thus it appears that a "collapse" has occurred.

The "measurement" of spin has a curious feature on the BB view. If in our example the magnetic field had been flipped 180 degrees (reversing the "up" and "down" paths) while the wave and position of the electron as it enters the field remained the same, the electron's motion would have been unaltered. This follows since the probability current in the field is unchanged by reversing the fields orientation. But then the very same electron which previously emerged on the "up" path would have taken the "down" path. The spin assigned to the electron as a result of the "measurement" depends on exactly how the measurement is made. It is known from work by Gleason, Kochen and Specker that any hidden variable theory which reproduces quantum mechanics must involve peculiarities of this kind-call "contextuality."[16]

The inevitability of contextuality is sometimes taken as showing that so called "hidden variable" theories like the BB view are impossible or at best awkward. But it is hard to see why contextuality should be counted against the BB view. According to it a particle's only intrinsil property is its position and that is not contextual—a position measurement can always be understood as revealing a pre-existing value. On the BB view a spin "measurement" is not really a measurement at all. It is an interaction between an electron and a magnetic field in which the motion of the electron depends on its wave's spin component. Since the equations of motion guarantee that subsequent "measurements" will agree with the initial one (assuming that the separated wave components do not overlap) the illusion that spin is an intrinsic feature of the particle is created.

In an n-particle system 6 (or 6*) guides the motion of the particles' 3-n configuration space (although each particle moves on a trajectory in 3-space). Because of this the motions of particles in certain states exhibit non-local effects. An example is the EPRB* state

EPRB* $\$_{12} = 1/\sqrt{2}\,[(|\uparrow_1\rangle\,|\downarrow_2\rangle - |\downarrow_1\rangle\,\uparrow_2\rangle)\,|\$_1\rangle\,|\$_2\rangle$

In this state particle 1 is in region R, particle 2 is in region L, and their spins are correlated. If particle 1 is passed through a magnetic field oriented in the z direction then it will move on the ''up'' or on the ''down'' path depending on its exact location as it enters the field. Suppose it moves ''up.'' Now this non-locally changes the dynamical properties of particle 2. If it were to enter a field oriented in the z direction then 6* constrains it to move ''down.'' It may be that particle 2 was traveling on a trajectory which would have gone ''up'' had the z-measurement on particle 1 not been made. So it seems we have non-local causality. This is incompatible with special relativity since it assumes a preferred frame relative to which the effect is instantaneous. But the probability assumption guarantees that relativity can not be observationally falsified. In particular, the result of a spin measurement on particle 2 is probabilistically independent of the component of spin measured on particle 1 so the non-locality cannot be exploited to send a superluminal signal.[17] So Bohm's realist interpretation of quantum theory leads to instrumentalism about special relativity.

This instrumentalism about relativity makes the BB view look old fashioned and unattractive from the point of view of contemporary physics. It has some other ''physically weird'' features as well. The wave characterizing a system S guides only the motion of those particles in S. Particles in other systems will not be effected by S's wave even if they are located nearby. Also, the particles are ''epiphenomenal'' with respect to the wave since it evolves in accordance with the Schrödinger equation and so independently of the locations of the particles associated with it. These features make quantum waves very unlike electromagnetic waves. Furthermore, the wave will typically guide its particles on highly ''non-classical'' trajectories. Moving with the probability fluid will generally involve accelerations which are not due to ''classical'' forces (electromagnetism etc.). This results in violations, at the level of individual particles, of conservation of momentum and energy. However, the theory also guarantees that these violations are not experimentally detectable. Related to this is the fact that on the BB theory the quantum mechanical observable for e.g. momentum becomes disconnected from a particle's momentum defined ''classically.'' There is no guarantee that the result of measuring the momentum observable will be the classically defined momentum. But, again, there is no experimental way to observe a difference between the value of the momentum observable and classical momentum.

The BB view describes a world which at the macroscopic level is metaphysically and even physically familiar. Particles and pointers always have definite positions and cats are always alive or dead. As long as quantum effects are not being amplified macroscopic objects are practically Newtonian. All this is done without the projection postulate and without dividing reality into the quantum and the classical. But down below, at the level of micro-systems the physics is weird. From a God's eye perspective the world according to the BB view must appear to be a vast conspiracy designed to deceive us and especially to deceive physicists. Experiment reveals a world which seems to be indeterministic, relativistic, in which spin (etc.) is an intrinsic property of particles, and which obeys conservation of energy and momentum. But according to the BB view this is all illusion. The God of the BB view doesn't play dice but he has a malicious sense of humor.

THE MANY MINDS VIEW

Everett's "Many Worlds Interpretation" (MWI) is another way of attempting to do without the collapse.[19] The MWI makes two physical claims: I) The state vector of a system, even if that system is the whole universe, completely describes the physical reality of that system. II) The state vector evolves only in accordance with Schrödinger's equation (or one of tis relativistic generalizations). Thus, it is like the BB view without the position variables. The problem, as we have seen, is how to square II with the appearances and especially with the definiteness of our experience. The MWI claims that if we understand the state of the universe in a certain way we will see that the collapse and the probability interpretation emerge as features of the theory. The state of the entire universe $ can be represented as a superposition thus:

$$\text{UNIV} \qquad |\$(t)> \; = c_1|A_1(t)> \; + \; c_2|A_2(t)> \; \ldots$$

where the A_i constitute a complete set of basis vectors that span the Hilbert space for the whole universe. The MWI suggestion is that each of the components of the superposition be thought of as representing a "world." As $(t) evolves according to Schrödinger's equation worlds diverge and sometimes merge. DeWitt's description of the process is:

> The universe is constantly splitting into a stupendous number of branches, all resulting from the measurement-like interactions between its myriads of components. Moreover, every quantum transition taking place on every star, in every galaxy, in every remote corner of the

> universe is splitting our local world on earth into myriads of copies of itself. (p. 161)

How can this dizzying multiplication of worlds save the appearances? Suppose that an observer M measures the x-spin of an electron e in an eigenstate of z spin. Let $\uparrow_z$ be the state z-spin "up", $\uparrow_x$ ($\downarrow_x$) be the state x-spin "up" ("down"), B_o be the state of belief prior to making the measurement and $B_\uparrow$ ($B_\downarrow$ be the state of M believing that x spin is up (down)). Before the measurement the state of the universe is $|@>|B_o>|\uparrow_z>$ (@ is the state of the rest of the universe.) At the conclusion of the measurement the state of the universe is

$$\text{BEL} \qquad 1/\sqrt{2}\,(|@>\,(|B_\uparrow>|\uparrow_x> + |B_\downarrow>|\downarrow_x>)$$

According to the MWI, the world has split into two worlds and M has split into two successors one of whom observes spin up and the other spin down. Each has a perfectly definite experience corresponding to the perfectly definite outcome in his world. Within each component of BEL the state appears to collapse since the Schrödinger dynamics guarantees that further measurements of the electron's spin will yield consistent results as long as the worlds do not merge. Finally, DeWitt says that "the conventional probability interpretation of quantum mechanics emerges from the formalism itself." (p. 163) We can see what he has in mind by considering a measuring device M capable of making repeated ideal measurements of x-spin and recording the result of the nth measurement in memory cell n. $B_n\uparrow(\downarrow)$ is the state of the nth cell which records that the nth measurement is $\uparrow(\downarrow)$. Suppose that an infinity of elctrons are each initially in state $c_1\uparrow + c_2\downarrow$). The interesting consequence is that as M measures each electron's spin recording the result in its nth cell the state of M × the electrons converges to a state \$ which is an eigenstate of the frequency operator $1/n(\mathrm{Sum}(P_i(\uparrow)))$ with eigenvalue c_1^2 (where $P_i(\uparrow)$ is the projection operator for $\uparrow_i$). This is supposed to make it true at each world that the probability of a measurement of x-spin yielding "up" is 1/2.

The reaction of most commentators, both physicists and philosophers, to the MWI is that it is too ontologically extravagant to be believable.[20] Extravagance doesn't bother us but we do think that DeWitt's version fails as an interpretation of quantum theory. The first problem is that the state UNIV does not uniquely determine the worlds. \$ can be represented in terms of infinitely many different sets of basis vectors (which are eigenvectors of different operators). Which representation determines the set of worlds? Different choices produce worlds in which different observables possess definite values and no choice results in a theory subscribing to I and II. First, any choice adds something *physical* to the state; the existence of worlds in which certain physical quantities have such and such values. Second, suppose that some set $\{A_i\}$ corresponding to operators $\{O_i\}$ is taken as basic. Then within any such world no observable incompatible with any of the O_i can possess a definite value. Any attempt to prepare a system in which such an operator does have a definite value must lead to a splitting of the observer's world. Thus no observer could experimentally confirm that the state of the universe or some part of the universe is an eigenstate of this observable. But this is quite contrary to the original idea that I and II completely describe the physical universe and its evolution. Also, the MWI involves an extreme violation of conservation of particles, mass etc. If every quantum transition leads to a splitting of the universe the mass of the universe is constantly increasing. This contradicts the claim that UNIV describes physical reality and Schrödinger's equation describes its evolution since Schröinger's equation conserves mass. Of course, within any world the mass of that world does not increase. But that is irrelevant since the Schrödinger equation is supposed to describe evolution of the whole universe of worlds. There are other problems with the MWI. For example, it is far from clear that it really can make sense of the probability claims of quantum theory. We will not discuss these further here but instead examine a near relative of the MWI which is not beset by these difficulties.[21]

Recall that subsequent to making the measurement observer O is in the state BEL. In that state M does not have a definite belief. Now this cannot be right. We know that a human being in BEL will report having a definite belief. This follows by linearity from the fact he will report having a definite belief if the initial state of the electron is either $\uparrow_x$ or $\downarrow_x$.[22] So if we grant him authority over the contents of his mental states then we must say that BEL is not the full story concerning M's beliefs.[23] Our proposal, the MMV, is to complete the story by adding to BEL not worlds but minds! We first make the physicalist assumption that there are certain physical states-states of brains which determine certain complete sets of mental states.[24] Call these physical states $\{B_i\}$ "eigenstates of mentality." An eigenstate of mentality determines all of the mental states of a mind associated with that brain (to the extent that mental states are objective). These physical states can be selected so as to form a complete set of basis vectors for the space appropriate for characterizing a human being M. Suppose that at t M's state $(t) is

MINDS $\underset{i}{\text{SUM}}\ c_1|B>|R_i>$

where the R_i are states of the rest of the world. According to the MMV to each B_i in MINDS there corresponds a set of minds whose mental states are determined by that state. For example, BEL is associated with two sets of minds, one whose minds believe that x-spin has just measured to be "up" and the other whose minds believe that it has just been measured to be "down."

There are various ways of accommodating quantum mechanical probabilities within the MMV. The simplest way is to suppose that a mind m_k associated with B_k in MINDS evolves probabalistically as $(t) evolves (deterministically) in accordance with the following prescription:

8. If $|B'_k>|R'_k>$ is the time evolution of $|B_k>|R_k>$ and $B'_k = a_1B_1 + \ldots a_jB_j + \ldots$ then the probability that m_k is associated with $B_j = a_j^2$.

This entails that it is an objective fact that a mind associated with a body about to make a measurement of x-spin on a z-spin will have a probability of 1/2 of "observing" (coming to believe) that the spin is "up."

We need to say a word about measurements in the MM view. If by "measurement" we mean just the physical interaction between M and S then on the MM view few measurements have definite outcomes. But we might consider a "measurement" to be complete only when a sentient being forms a belief about the outcome. Such beliefs will almost always be mistaken (since no definite outcome has occurred). However, the MMV guarantee that a mind evolving in accord with 8 will develop beliefs consistently so if it believes that, e.g., x-spin is "up" after a measurement, subsequent measurements will confirm this result.

We have little doubt that the MMV will invoke in most readers an "incredulous stare." We hope that stare is sufficiently penetrating to notice the following features: First, as advertised the MMV validates I and II. UNIV is the complete physical description of the universe and states evolve only in accord with Schrödinger's equation. Second, the view saves the appearances, that is, it accounts for (i), (ii), and (iii). While a physical experiment may not have a definite outcome (the pointer may be in superposition of locations) any mind observing the pointer will experience a definite outcome. The consistency of subsequent measurements can be used here (as in the MWI and BBV) to account for the appearance of a collapse. And quantium mechanical probabilities refer to the probabilistic evolution of minds. Third, because the only dynamical equation governing physical change is Schrödinger's equation the MMV describes a physical world which is completely deterministic, which conforms to the usual conservation laws, and, perhaps somewhat surprisingly, in which all interactions are completely local. The first two points are obvious so we will comment only on the third by explaining how the MMV describes EPR situations. Suppose that an observer L measures the x-spin of one of a pair of electrons in an EPR state. According to the MMV L's minds evolve into two sets; those that believe that the result is ''up'' and those that believe that the result is ''down.'' So far everything is completely local since Schrödinger's equation characterizes purely local processes. Suppose also that another observer R measures the x-spin of the other electron. His minds undergo a similar evolution. Should L and R meet and compare results the Schrödinger equation guarantees that every mind will believe that the results are anti-correlated in the usual way. Had R decided to measure some other component of spin then the probability that the minds will obtain anti-correlated results are also the usual quantum mechanical ones. In this account every change is completely local. Is this a violation of Bell's theorem? Not at all. Bell assumes that in the EPR experiment the measurements have definite outcomes-e.g. electron 1 is spin up. But on the MM view the electron has no definite spin. And if any sentient observer measures the electron's spin he will come to have a definite belief about it; indeed he will have minds which believe that spin is up and minds that believe that spin is down.

We conclude with a brief comparison between the BB view and the MM view. The first point to make is that the two views are empirically equivalent in the following limited sense: they agree on the probabilities of outcomes of whatever they both take to the measurements.[25] Of course, the two views characterize measurements differently. On the BB view a measurement is not complete until a result is recorded in the position of something and on the MM view it is not complete until the result is recorded in certain states of an observer's brain. Here we have relativity of the description of data to theory of a very interesting sort. We also have an example of the underdetermination of theory by data on a grand scale.

Both views are realist in that each claims that there exists a mind-independent reality. They agree that part of that reality includes the quantum mechanical state and that it evolves in accordance with Schrödinger's equation. Where they differ is in what they add to the quantum mechanical state in their attempts to save the appearances. The BB view adds particles with definite positions and a deterministic law governing their motions. The MM view adds minds and a probabilistic law governing their evolutions. On the BB view the macroscopic world is, more or less, as we think of it pre-quantum mechanically. Physical objects always possess definite positions and macroscopic objects are practically Newtonian. On the other hand, at the micro-level the world is, from the point of view of contemporary physics, incredibly weird. There is non-local (though undetectable) causation. There is the wave-particle interaction which is unlike anything previously encountered and which leads to (undetectable) violations of conservation principles. The observational validity of the indeterminacy relations, special relativity, conservation laws and so on seem to be designed to mislead physicists. In contrast, the MM view is completely in accord with conservation principles and with special relativity. But from the point of view of our pre-quantum mechanical view of macroscopic reality it is bizarre. The macroscopic world as we normally conceive of it doesn't exist or exists only in our minds! That experiments have definite outcomes (that the cat is really alive) is an illusion. The appearance of non-locality in experiments at the quantum level is also an illusion. While the totality of minds is physically determined the identity of a mind through time is not physically determined. So the MM view is committed to a kind of non-physicalism which may strike some as philosophically unattractive.[26] On a scorecard, it seems to us that BB wins for those who like their metaphysics ordinary and their macroscopic world familiar. The MM view wins for those who want to preserve the elegance of contemporary physics and don't mind adopting a radical metaphysics.

Both the views described here have an advantage over the standard interpretation. They, unlike it, are completely explicit about what really exists and how what exists evolves. There is no shifty division between the macro and micro worlds and no temptation to lapse into irrealist talk. Although they tell odd stories about EPR and measurement the stories they tell are perfectly clear. We think that this advantage earns our two views a closer look from philosophers of physics than they have yet received.

NOTES

[1] Bohm's formulations can be found in Bohm, D., *Phys. Rev.* 85 (1952) and Bohm and Hiley, B., *Found. Phys.* 14 (1984). Bell's formulations can be found in Bell, J.S. *The Speakable and Unspeakable in Quantum Mechancis* Cambridge, 1987. Page references to Bell's papers are to this book.

[2] Albert, D. and Loewer, B. "Interpreting the Many Worlds Interpretation" *Synthese,* December 1988.

[3] The standard formulation originates in von Neumann, J. *Mathematical Foundations of Quantum Mechanics*, tr. R.T. Beyer, Princeton: Princeton University Press, 1955.

[4] Einstein, A., Podolsky, B., and Rosen, N., *Phys. Rev.* 47 (1985).

[5] Bell, J.S. "On the Einstein-Podolsky-Rosen Paradox." *Physics* 1 (1964) 195-200.]

[6] Bell op. cit. p. 55.

[7] This is a straightforward consequence of the linearity of the Schrödinger equation.

[8] There is an observable Q such that CAT as an eigenstate of Q but neither a_ixB_i is an eigenstate of Q.

[9] The standard interpertation is usually called "The Copenhagen Interpretation" and is associated with Bohr and Heisenberg. We refrain from using that name since the exact nature of the Copenhagen interpretation is controversial and our "standard interpretation" is certainly much cruder than Bohr's subtle views.

[10] Bohr, N. in *Albert Einstein, Philosopher-Scientist*. P.A. Schlipp, ed., Tudor, N.Y. (1949).

[11] Einstein, A., Letter to E. Schrödinger, May 1928.

[11'] Recently Ghirardi, Rimini, and Weber [*Phys. Rev. D*. 34, 1986] have proposed a modification of quantum mechanical dynamics which amounts to supposing that there is always a small probability of a collapse (of the wave in position space). The probability is sufficiently small so as to be undetectable for microscopic systems but is large for a macroscopic system like the measuring device. While their idea is initially attractive it has problems of its own. See Bell, J. "One There Quantum Jumps" pp. 201-212 and Albert, D. and Vaidman, L., "On a New Theory of the Collapse of the Wave Function," Proceedings of the Workshop on Formelations of Quantum Theory, George Mason University, (1988).

[12] Daneri, A., Loinger, A., and Prosperi, G.M. (1962). "Quantum Theory of Measurement and Ergodicity Conditions." *Nuclear Physics*, 33, 297-319. Their attempt to solve the measurement problem has been defended and later criticized by Nancy Cartwright in *How the Laws of Physics Lie*. Despite the fact that the proposal has been "refuted" a number of times one continues to find it. A recent example is *Niels Bohr's Philosophy of Physics* [D.R. Murdoch *Cambridge*, 1987]

[13] A simple way of arguing for their conclusion is this. In order to experimentally distinguish between CAT and either of A_ixB_i we need to find an observable Q whose operation O is a projection operator for CAT. If M + S interacts with some other particle P, say a photon or air molecule, so as to correlate the position of the particle with the position of the pointer (the correllated particle states being C_i then the resulting state of M + S + P will be $1/2SUMA_ixB_ixC_i$. It this state Q is random and so indistinguishable from the mixture $1/2SUMA_ixB_i$. Since it is very likely that M + S interacts with some other particle in this way CAT is experimentally indistinguishable from the mixture. However, we should note that there is nothing in quantum theory to preclude the *possibility* of isolating M + S. In that case it would be, as mentioned in footnote 8 experimentally possible to distinguish CAT from the mixture.

[14] The status of the probability assumption 7 in the BB view is note entirely clear. The assumption of an initial random selection is made to justify the ususal quantum mechanical probabilities as epistemic probabilities. Since this assumption is implausible the justification is weak, at best. Another way of attempting to a justification would be to derive 7 as an appropriate "ignorance" distribution (similar to the justification of probability distributions in classical mechanics). But we know of no such derivation which is successful.

[15] See Bohm *Phys. Rev.* 85, (1952) and *Wholeness and the Implicate Order* and Bell op. cit. The qualification to Positionism is a specification of the way observations are to be described. Given this qualification standard quantum theory and the BB theory make exactly the same predictions—modulo the remark below—concerning where pointers will end up (or their probabilities), the distribution of ink in physics journals reporting the experiments etc. This claim requries qualification since the standard theory postulates that some processes evolve in accordance with 5 although it is vague about exactly which. Since on the BB theory there is no collapse, at any point at which standard QM postulates a collapse the two theories will differ. However, since collapses involve interactions with macroscopic objects usually the predictions are, for reasons related to the Prosperi et. al., practically indistinguishable.

[16] For a discussion of the results of the various "No hidden variables theories" see Redhead, M. *Incompleteness, Nonlocality, and Realism: A Prolegomenon to the Philosophy of Quantum Metaphysics*. Oxford; Clarendon Press. (1987)

[17] The probability of obtaining "up" ("down") on a z-measurement of particle 2 is 1/2 no matter what component of spin is measured on particle 1. But, as in standard quantum theory, the outcome of the measurement of 2 is not independent of the component of spin measured on 1 and the outcome of that measurement.

[18] This nice way of putting matters is due to Hilary Putnam. The existence of non-local influences, even if they cannot be used to send superluminal signals, is often thought to be a defect of the BB view. The standard interpretation also exhibits non-locality since, as we saw in the EPR situation, the collapse instantaneously changes the quantum state of a spatially extended system. The non-locality in this case seems to be of a gentler kind-Shimony calls it ''passion at a distance''—since it changes what can be meaningfully predicated of a system and its parts but does not, as in the BB view, change the value of a physical quantity e.g. velocity. On the standard view the causal counterfactual ''If particle 1's z-spin had not been measured then particle 2 would have moved ''down'' not ''up'' is false.

[19] The Many Worlds Interpretation was invented by Hugh Everett and developed and defended by, among others, DeWitt, Wheeler, Deutch, and Hawking. The main papers concerning this interpretation are collected in DeWitt, B., and Graham, N., *The Many Worlds Interpretation of Quantum Mechanics* Princeton University (1973). There are some important differences between various versions of the interpretation. The one we call ''the splitting worlds view'' is closest to DeWitt's view.

[20] See Gibbens, Peter *Particles and Paradoxes*, Cambridge for a typical philosophical reaction to the MWI.

[21] Further criticisms can be found in Healy, R. ''How Many Worlds'' *Noûs* 18 (1984) and in our ''Interpreting the Many Worlds Interpretation''.

[22] It is a theorem of the formalism that if A and A* are eigenstates of some observable Q then any superposition of A and A* is an eigenstate of Q. In this case the observable is the one with values ''reports a definite result'' and fails to report a definite result.

[23] This argument depends on the fact that if A_1 and A_2 are each eigenstates O then any superposition of these states is an eigenstate of O. See ''Interpreting the Many Worlds Interpretation'' for further discussion.

[24] Rule 8 is an over simplification. It applies only as long as there is no interferences among the branches of MINDS. That is, it applies only under the condition that for all k and j in the time evolution of MINDS if R'_k is not orthogonal to R'_j the $a_{ik} = 0$ if $a_{ij} \neq 0$. See Albert, D., and Putnam, H. ''Further Reflections on Schrödinger's Cat'' (forthcoming) for the general probability rule.

[25] A precise statement of the sense and extent to which the BB and MM views are empirically equivalent is more detail than can be gone into here. We will provide the exact statement in a forthcoming paper.

[26] Some of this non-physicalism is eliminable if one is willing to explain away our sense of personal continuity into the past and future. See ''Interpreting the Many Worlds Interpretation'' op. cit.