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CAN THE DECOHERENCE APPROACH HELP TO SOLVE THE MEASUREMENT PROBLEM?

ABSTRACT. This work examines whether the environmentally-induced decoherence approach in quantum mechanics brings us any closer to solving the measurement problem, and whether it contributes to the elimination of subjectivism in quantum theory. A distinction is made between ‘collapse’ and ‘decoherence’, so that an explanation for decoherence does not imply an explanation for collapse. After an overview of the measurement problem and of the open-systems paradigm, we argue that taking a partial trace is equivalent to applying the projection postulate. A criticism of Zurek’s decoherence approach to measurements is also made, based on the restriction that he must impose on the interaction between apparatus and environment. We then analyze the element of subjectivity involved in establishing the boundary between system and environment, and criticize the incorporation of Everett’s branching of memory records into the decoherence research program. Sticking to this program, we end by sketching a proposal for ‘environmentally-induced collapse’.

1. IN SEARCH OF OBJECTIVISM

The history of the interpretations of quantum theory, as is well known, has been dominated by the views of Bohr, Heisenberg, von Neumann, etc., which have been generically classed within the ‘orthodox’ interpretation of quantum mechanics. However, the views of such authors have slight differences, and each of these views has changed along the decades.

One of these changes is related to the problem of idealism: what is the role of the observer in the constitution of reality? In the 1930s, what may be called the *subjectivist* view was quite popular: human consciousness would be ultimately responsible for the ‘collapse’ of the quantum state. The clearest defense of this view was given by F. London and E. Bauer (1939), while similar views have been attributed to von Neumann, Jordan, and von Weizsäcker before the war (see Jammer 1974, pp. 160–162, 479–486).

In the early 1950s, however, defenders of *objectivist* views started publishing their criticisms to subjectivism, declaring that it was possible to describe the collapse of the wave packet as a thermodynamical process involving the macroscopic measuring instrument initially in a metastable

Synthese **113:** 323–346, 1998.

state, without any need to introduce the human observer. Some of these early objectivists were Jordan, Bohm, Ludwig, H.S. Green, Taketani, and Feyerabend (see Jammer 1974, pp. 486–493; d'Espagnat 1976, pp. 186–196). By 1957 the so-called 'measurement problem' became one of the hottest issues of dispute in the foundations of quantum mechanics. One may say that subjectivism became a minority view, defended ocasionally by important physicists such as Heitler or Wigner, and the consensus seemed to be that quantum physics *could be* described independently of the human observer. But the problem of exactly how this could be done remained subject to debate.

2. COLLAPSE AND DECOHERENCE

The strategy of the objectivist approaches was to describe thermodynamically the process of amplification that occurs during measurement and show that the interference terms characterizing quantum states vanish in the limit of infinite-sized apparatuses and infinite times (see for instance Green 1957; Daneri *et al*. 1962). However, an explanation for the vanishing of interference terms in statistical ensembles does not explain the collapse of a pure state to another pure state associated to individual object systems. What has been explained (rightly or wrongly) by different thermodynamic approaches is what may be called 'decoherence', and such explanations do not imply an explanation for individual 'collapse'.

This point has been made for instance by Bell (1990, p. 25): 'The idea that elimination of coherence, in one way or another, implies the replacement of "and" by "or" [$\Psi_1\Psi_1^*$ and $\Psi_2\Psi_2^*$ and ... by $\Psi_1\Psi_1^*$ or $\Psi_2\Psi_2^*$ or ...], is a very common one among solvers of the "measurement problem". It has always puzzled me'. This also seems to be one of the points stressed by Bub (1968, p. 514) in his criticism of the thermodynamic approaches. The formal distinction between decoherence and collapse may be found in Süssmann (1957), who distinguished clearly between what he called 'division' (decoherence) and 'reading' (the collapse which follows decoherence).

In summary, we are adopting the following convention. *Decoherence* is a statistical concept, involving the transition from a pure state to a 'mixture', and the disappearance of interference terms. *Collapse* refers to an individual system, and it describes a transition from a pure state to another pure state. This distinction is usually not made in the literature (for a recent example, see the otherwise interesting article by Albrecht 1993), and it is explicitly denied by some interpretations of quantum mechanics.[1]

We will describe mathematically both of these processes in the following section, which deals with the ‘projection postulate’.

Let us now explore the relation between the two by means of a didactical example. Consider an electron two-slit thought-experiment, in which an interference pattern forms on a detecting screen. Interference arises because the wave amplitudes going through slit A and slit B are ‘coherent’, having the same wavelength and a fixed phase shift. Any process which disturbs the coherence of the waves (turbulence, scattering photons, etc.), introducing random phase shifts, washes out the interference pattern (Bohm 1951, pp. 600–604). This is a process of decoherence. Collapse, in this case, may be associated with the presence of a single electron in some small region of space, such as the region delimited by a bright spot on a scintillation screen (or in a detector placed after one of the slits). In this case, collapse is associated with localization of a single object (or, as a mnemonic rule, with the *existence of a particle*, according to de Broglie’s and Bohm’s hidden-variable theory), while decoherence is associated with *random phases* (or to the disturbance associated with the uncertainty principle; see Bohm 1951, p. 131).[2]

We have stressed that an explanation for the statistical behavior of an assembly of particles might be given without explaining what happens at the level of individual particles. In short: *an explanation for collapse implies an explanation for decoherence, but an explanation for decoherence doesn’t imply an explanation for collapse*.

Does that mean that decoherence and collapse must be associated to *distinct* physical processes? Not necessarily. What we have are thermodynamic models that explain decoherence (including the more recent models based on environmentally-induced decoherence, to be examined in this paper) but don’t explain collapse. However, such approaches could be incomplete! If an explanation for decoherence is accepted, shouldn’t it also be applied to an individual quantum object? In certain simple examples, decoherence can be linked to collapse. Can this link between decoherence and collapse be generalized? We will consider this possibility at the end of this paper, with the sketch of a program for ‘environmentally-induced collapse’.

3. THE PROJECTION POSTULATE

If a quantum system is in an eigenstate of the operator corresponding to the observable being measured, the outcome of the measurement will be the eigenvalue associated with that eigenstate. However, if the system is in a superposition of such eigenstates, the outcome will be unpredictable, and all that quantum theory can give are the probabilities for the different outcomes. If the system is not destroyed by the measurement, and if the interaction fits into the so-called ‘measurement of the 1st kind’, then the quantum state after the measurement will be the eigenstate associated to the measurement outcome, or more generally (to include degeneracies), the normalized projection of the original state onto the eigensubspace associated with the outcome. This rule is known as the *projection postulate*, and it originated with Dirac and von Neumann, and was later formalized in degenerate cases by Lüders and Ludwig.

Let us express this mathematically for finite-dimensional spaces and for the non-degenerate case. Consider a quantum object in a pure state $\sum_i a_i \cdot |\phi_i\rangle$. If a measurement of some observable represented by $\hat{O} = \sum_i \gamma_i \cdot \hat{P}[\phi_i]$ is performed, where $\hat{P}[\phi_i] \equiv |\phi_i\rangle\langle\phi_i|$ stands for the projection operator onto the subspace spanned by $|\phi_i\rangle$, and the eigenvalue γ_k is obtained as the probabilistic outcome of the measurement, then the projection postulate says that the object state right after the measurement (of the ‘1st kind’) is completed is $|\phi_k\rangle$. For a single quantum object, we may therefore write:

$$(1) \qquad \left|\sum_i a_i \cdot \phi_i\right\rangle \xrightarrow{P.P.} |\phi_k\rangle \quad \text{with probability } |a_k|^2.$$

For an ensemble of measurements of the same observable performed on the same initial pure state (that is, each measurement being performed on a different single object, all prepared in the same pure state), one may represent the statistical transition described by the projection postulate as follows:

$$(2) \qquad \hat{P}\left[\sum_i a_i \cdot \phi_i\right] \xrightarrow{P.P.} \sum_k |a_k|^2 \cdot \hat{P}[\phi_k].$$

Equation (1) should be associated with state collapse, while Equation (2) with decoherence. Given that Equation (1) is applicable to each individual system in an ensemble, one obtains the statistical result of Equation (2). The converse, however, is not valid, as pointed out in Section 2.

4. THE MEASUREMENT PROBLEM

Having distinguished between collapse and decoherence, which correspond to the individual and statistical versions of the projection portulate (Equations 1 and 2), one may inquire into the physical origin of these processes. How does the final state described by the projection postulate arise? How do such indeterministic state transition take place? These questions are general statements of the well-known *measurement problem*. Notice however that they may refer either to decoherence or to collapse (which is a harder problem). Besides this division between a statistical and an individual measurement problem, another division may be made: (i) ‘Characterization problem’ (term adapted from Cartwright 1983, p. 196): at what stage of the measurement, understood as a physical process, does the collapse of the state vector (or decoherence) occur? Is it during amplification? During conscious observation? (ii) ‘Completeness problem’ (ambiguous term used by Fine 1973, pp. 568–570): can the apparently indeterministic state transition described by the projection postulate be explained by the unitary evolution (the Schrödinger equation) which applies to closed quantum systems, plus some ingenious model of the measurement process?

The subjectivist views in the 1930s solved the characterization problem (individual case) by appeal to human consciousness. The objectivists in the 1950s and 1960s solved it by appeal to the thermodynamic process associated with amplification, although, as we have seen, what was really being derived was decoherence, not individual collapse. Furthermore, around 1966 it was realized that one could have state collapse without amplification, in the so-called null-result measurements (Jammer 1974, p. 493).

As regards the completeness problem, defenders of the thermodynamic approach considered that the projection postulate was not a fundamental rule of quantum mechanics anymore, since its effect could be derived from the Schrödinger equation in the limit of an infinite-sized apparatus, and of an infinite long time. But again, as we have been arguing all along, they could only claim to have justified Equation (2), not Equation (1). Furthermore, there was the problem of justifying such limits for finite-sized apparatuses and finite time spans.

That the projection postulate could not be eliminated, for finite-sized apparatuses, was rigorously shown by means of the ‘insolubility proofs’ (term introduced by Fine 1970) to the completeness problem. Such proofs were inaugurated by von Neumann ([1932] 1955, p. 438–439), and reinstated by Wigner (1963) and others in the 1960s. If a solution were found for the completeness problem, then one could admit that nature is deterministic, but in a ‘hidden’, *cryptodeterministic* way: measurement outcomes would be unpredictable because we can never know what the exact state of the measurement apparatus is (see von Neumann, p. 438; term coined by

Whittaker 1943, p. 461). The projection postulate (Equation 1) would be reducible to the unitary evolution described by the Schrödinger equation.

To show that the completeness problem is soluble, one would have to construct a composite quantum system (object plus apparatus) satisfying certain hypotheses: (1) The *macroscopic apparatus* may be adequately described as *a quantum system*, either pure or mixed, associated with a finite dimensional Hilbert space. (2) *Unitarity hypothesis*: the composite system consisting of object and apparatus may be taken to be *closed*, so that its temporal evolution is unitary. (3) *Pointer assumption*: the different measurement outcomes correspond to distinct final states of the apparatus ('pointer states'). (4) *Solubility condition*: roughly speaking, one would require that for a single measurement on any initial object state, the final apparatus state be a pointer eigenstate; the insolubility proofs use a less stringent statistical condition, allowing the apparatus to be initially described as a mixture, and only requiring that the final composite density matrix be diagonal in the pointer state representation. (5) *Kind of measurement*: one must characterize the class of measurements being considered: 1st kind, 2nd kind, projection-valued measures or positive operator-valued measures.

A measurement that would satisfy the above conditions would constitute a solution to the completeness problem. The insolubility proofs, however, show that such measurements cannot be defined[3]. Representing the unitarity hypothesis (2) by **U**, the definition of measurement (5) as **M**, the solubility condition (4) as **S**, and the additional hypotheses (1, 3) as **H**, one may represent the general scheme of the insolubility proofs as: **H**, **U**, **S** $\rightarrow \neg$**M**, where '→' stands for implication and '¬' for negation. Accepting **H** and **U**, this means that there are no measurements (of a certain type) that fulfill the solubility condition: **H**, **U**, **M** $\rightarrow \neg$**S**.

To summarize, the insolubility proofs showed that for finite closed composite systems, the projection postulate (either the individual or the statistical cases) cannot be reduced to the unitary evolution described by the Schrödinger equation, which is known to work for closed microscopic systems. Neither collapse nor decoherence is consistent with the above set of hypotheses.

5. THE OPEN-SYSTEMS APPROACH

In the 1970s, various novel approaches were given to the measurement problem, but we will be concerned here with what was then called the *open-systems* approach. The central claim of this view is that *macroscopic systems such as measuring apparatuses are never closed, but interact* *significantly with their environment* (Zeh 1970; Baumann 1970; Wigner 1983). This implies that the states representing such systems do not evolve unitarily (do not obey the Schrödinger equation). The truth of this claim could amount to a way out of the insolubility proofs, which are only valid for closed systems. Thus, the open-systems approach became a serious candidate for furnishing an objectivist ‘solution’ to the measurement problem.

The origin of this thesis of the ‘openness of macroscopic systems’, or *open-systems thesis*, might be traced back to Burbury’s (1894–1895) solution to the problem of irreversibility in classical statistical mechanics. An enclosed gas would not exhibit recurrence because of the thermal fluctuations originating in the external environment. Borel (1914, pp. 178–180) showed that the gravitational effect of a small displacement of a small body in a faraway star was sufficient to alter significantly the microscopic state of the enclosed gas. The thesis that a quantum system, at least during its interaction with a macroscopic apparatus, could not be isolated from the rest of the universe had been emphasized by some authors within the orthodox interpretations (Bohm 1951, pp. 138–140; Heisenberg 1958, p. 53). It also formed one of the principles of Everett’s (1957) notion of ‘relative states’.

The use of the open-systems thesis to solve the measurement problem in an exact way suffers from one big problem, which we will call the ‘problem of the closed universe’. Given an open system, one can always choose a larger system which includes the system and its environment. If this enlarged system is open, one can go on choosing larger and larger systems until one arrives at the universe, which is considered a closed system. So for this enlarged closed system the insolubility proofs apply, and the open-systems approach must fail as an exact solution to the completeness problem.

In view of the closure of the universe as a whole, the open-systems approach could only furnish an approximate solution to the measurement problem. Steps towards the fulfillment of this project would be given by use of the partial trace, and by the notion of ‘environmentally-induced decoherence’.

6. THE PARTIAL TRACE

If an open system cannot be described by Schrödinger-like equations, how can it be described? The adequate description, according to the open-systems view, would be to consider an enlarged closed system consisting of the object (the open subsystem) and the environment, describe its unitary evolution by spelling out the interaction between the object and environment, and then, at the time of interest when supposedly an observation would take place, eliminate the environmental coordinates by means of the mathematical technique of taking a ‘partial trace’.

To illustrate the use of the partial trace, consider that the object and the environment are each represented by a finite-dimensional Hilbert space, $\mathbf{H_o}$ and $\mathbf{H_e}$. According to a theorem proved by E. Schmidt (1907), *any* pure composite state $|\Psi\rangle$ in $\mathbf{H_o} \otimes \mathbf{H_e}$ can be represented in the following way:

$$(3) \qquad |\Psi\rangle = \sum_i a_i \cdot |\phi_i \otimes \varepsilon_i\rangle,$$

for *some* orthonormal set of basis states $|\phi_i\rangle$ and $|\varepsilon_i\rangle$, respectively in $\mathbf{H_o}$ and in $\mathbf{H_e}$. This pure state corresponds to the following density operator:

$$(4) \qquad \hat{W} = \hat{P}\left[\sum_i a_i \cdot |\phi_i \otimes \varepsilon_i\rangle\right] = \sum_{ij} a_i a_j^* \cdot |\phi_i \otimes \varepsilon_i\rangle\langle\phi_j \otimes \varepsilon_j|.$$

The *partial trace* of $|\Psi\rangle$ over the environmental states $|\varepsilon_i\rangle$ is defined as:

$$(5) \qquad \mathrm{Tr}_\varepsilon(\hat{W}) = \sum_k \langle\varepsilon_k|\hat{W}|\varepsilon_k\rangle.$$

Applying this definition to Equation (4) yields:

$$(6) \qquad \mathrm{Tr}_\varepsilon(\hat{W}) = \sum_k |a_k|^2 \cdot \hat{P}[\phi_k].$$

The resulting mixture is called a ‘reduced density operator’ (Blum 1981, pp. 65–67) or an ‘improper mixture’ (d’Espagnat 1976, pp. 58–62).

Reduced density operators were introduced by von Neumann ([1932] 1955, pp. 424–425): ‘In fact, an observer who could perceive only [the object system] I, and not [the apparatus system] II, would view the ensemble of systems I + II as one such of systems I.’ U. Fano (1957, pp. 86–87) described the application of partial traces when two systems a and b interact, but when ‘practical interest [. . .] centers in the resulting state of a only, irrespective of what has become of b’.

7. GENERALIZED MASTER EQUATIONS AND DECOHERENCE

So the strategy for describing the temporal evolution of an open quantum system was to write out the equation for unitary temporal evolution of the overall system (object + environment), and then eliminate the environmental coordinates by means of a partial trace. The resulting equation for the reduced density operator representing the open object system is called a *generalized Master equation* (Blum 1981, p. 169).

This strategy was apparently pioneered by Wangsness and Bloch (1953, p. 730) in the treatment of the relaxation of the spin orientation of a fixed atomic nucleus (system a), where system b consisted of the all surrounding particles, through which the effects of the interaction with system a would dissipate quickly and not react back onto a. After spelling out the unitary time evolution of the composite system, they applied a partial trace to the coordinates of system b, thus obtaining (with the help of certain approximations) the temporal evolution of the nucleus' reduced density operator (see also Fano 1957, pp. 90–92).

In the following years, the use of partial traces to eliminate environmental coordinates and derive generalized Master equations was greatly developed by many researchers, both in the Heisenberg picture (Senitzky, Mori) and in the Schrödinger picture (Nakajima, Zwanzig) (see Haake 1973). These works added to the unitary von Neumann equation (i.e., the Schrödinger equation for density operators) a second term that describes the damping or energy dissipation of the open object system.

Feynman and Vernon, in 1964, using the path integral formalism, derived an additional term related to fluctuation or Brownian motion. They assumed that the environment consisted of an infinite number of harmonic oscillators, but were unable to integrate their complicated expression. Caldeira and Leggett (1983) achieved instant fame by deriving a closed analytic expression for this third term, following Feynman and Vernon's method, and assuming a specific mode density for the harmonic oscillators of the environment.[4] Hepp and Lieb had solved a particular case in 1973 (see Omnès 1992, p. 355).

The reduced density operator of Caldeira and Leggett, expressed in the position representation, exhibited off-diagonal terms that decrease exponentially in time. This is a manifestation of *decoherence*: the initial pure object state, represented by a reduced density operator that is a projector (for which $\mathrm{Tr}(\hat{W}_0^2) = 1$), evolves into a mixture with a higher entropy, not associated with a projector but with a 'non-idempotent' density operator (for which $\mathrm{Tr}(\hat{W}_0^2) < 1$). This process takes place in very short 'decoherence times', which are inversely proportional to the mass of the object. The object system, initially in a pure superposition of position eigenstates, is forced by the environment into a 'classical' state, described by the diagonal density operator: this would allegedly correspond to some unspecified well-defined (localized) position state. While Caldeira and Leggett were concerned with the effect of an ‘internal environment’ of electrons upon the coherent system of superconducting electrons, Joos and Zeh (1985) treated the case of the effect of an ‘external environment’ of particle collisions upon a macroscopic body (see reviews by Zurek 1991, and Omnès 1992, pp. 354–357).

The application of these techniques for describing the measurement apparatus as an open quantum system and for studying the measurement problem is known as the ‘decoherence approach’. Following the initial proposal of Zeh (1970, 1971), this approach was systematized by Zurek (1981, 1982). One of the important sympathizers of the program was Wigner (1983, p. 58), who drew back from his earlier subjectivist position. Zurek’s (1991) review article in *Physics Today* helped to popularize the decoherence approach, and to stimulate criticisms (see the letter exchange in *Physics Today*, 1993).

8. PARTIAL TRACE AND THE PROJECTION POSTULATE

In the beginning of the 1980s, Nancy Cartwright (1983, pp. 195–206) proposed that the measurement problem could be dissolved simply by recognizing that the generalized Master equation (with the dissipation term, but not yet with the fluctuation term associated with decoherence) is the fundamental equation of quantum mechanics, and not the Schrödinger equation. Since both unitary and non-unitary (irreversible) evolutions arise as particular solutions to the Master equation, the problem of establishing in what circumstances a unitary evolution occurs and in what circumstances it doesn’t (when a collapse occurs or not) would not be a fundamental question anymore.

Two general criticisms can be made against Cartwright’s thesis. First, as discussed in Section 2, generalized Master equations can only describe statistical decoherence, not individual collapse. The second criticism is the following: the generalized Master equations are derived from the unitary evolution of the composite system (object plus environment) and from the application of a partial trace to eliminate environmental coordinates (besides other approximations). However, the use of the partial trace is equivalent to the use of the projection postulate. So the Master equation is derived from both the Schrödinger equation (or the equivalent unitary equation in the Heisenberg picture) and the projection postulate, and cannot be considered a fundamental equation of quantum mechanics.

The second criticism hinges on the following thesis: *taking a partial trace amounts to the statistical version of the projection postulate*. This can be illustrated by comparing the right-hand sides of Equations (2) and

(6). We see that for the simple case in which the initial states are pure, performing an ensemble of measurements of the observable corresponding to the operator $\hat{O} = \sum_i \gamma_i \cdot \hat{P}[\phi_i]$ yields a final density operator that is the same as the reduced density operator obtained when a partial trace over environmental states $|\varepsilon_i\rangle$ is performed on the composite state $|\Psi\rangle$ of Equation (3). It is true that applying the projection postulate and taking a partial trace are quite different mathematical operations, but the way these are used to describe the process of measurement and environmental monitoring amount to the same effect: the non-unitary evolution of a pure state to a non-idempotent mixture. Our claim is twofold: (i) whenever a partial trace is taken, the resulting mixture can also be obtained by applying the projection postulate to an ensemble of measurements corresponding to a suitable observable; (ii) the physical process described by these different mathematical operations is the same. Such theses will not be rigorously proven, but a more detailed comparison of the use of both techniques in the process of measurement will be given in the following section. The thesis that 'taking a partial trace amounts to applying the projection postulate' does not only serve to criticize Cartwright's view, but will also imply that the use of partial traces in the open-systems approach cannot solve the completeness problem. It also implies that one is not justified in claiming that the projection postulate is unnecessary for describing certain processes (such as the quantum Zeno effect) merely by presenting a generalized Master equation for the process. The connection between taking a partial trace and applying the projection postulate has already been pointed out by some authors (Jauch 1964, p. 313; Zeh 1971, pp. 265, 268–269; Grossman 1974, p. 339).

9. MEASUREMENT AND ENVIRONMENTALLY-INDUCED DECOHERENCE

Let us now turn to a more detailed comparison of the projection postulate with the partial trace technique, in the description of the process of measurement.[5] Consider first the application of the projection postulate. In the usual treatments of the completeness problem, the cut between the quantum system and the classical system is shifted to include the apparatus (or part of it) as a quantum system, forming a 'composite quantum system' in $\mathbf{H_o} \otimes \mathbf{H_a}$. The process of measurement is then described in two steps. First, the initially uncorrelated composite system (object plus apparatus) evolves unitarily into a correlated state, according to an evolution operator $\hat{U}_1$:

$$(7) \qquad \left|\sum_i a_i \cdot \phi_i\right\rangle \otimes |\xi_0\rangle \xrightarrow{\hat{U}_1} \left|\sum_i a_i \cdot \phi_i \otimes \xi_i\right\rangle.$$

The evolution operator $\hat{U}_1$ can be quite general, as long as it satisfies some minimal requirements in order to be called a ‘measurement’ (see Pessoa 1994). In Equation (7), however, we chose to represent a measurement of the 1st kind. The apparatus pointer states $|\xi_i\rangle$ do not arise naturally from the formalism, but are given ‘empirically’ by the macroscopic behavior of the measuring instrument.

The projection postulate is then applied to the evolved state. In the case of a measurement on a single system described by the right-hand side of Equation (7), the projection is made onto one of the subspaces $\mathbf{H_o} \otimes |\xi_k\rangle$ according to the outcome obtained, since only the apparatus is observed. For the individual case, we may write:

$$(8) \qquad \left|\sum_i a_i \cdot \phi_i \otimes \xi_i\right\rangle \xrightarrow{P.P.} |\phi_k \otimes \xi_k\rangle \quad \text{with probability } |a_k|^2.$$

For an ensemble of measurements (such as that representing the measurement performed on a beam of non-interacting particles prepared in the same pure state), the projection postulate yields (statistical case):

$$(9) \qquad \hat{P}\left[\sum_i a_i \cdot \phi_i \otimes \xi_i\right] \xrightarrow{P.P.} \sum_k |a_k|^2 \cdot \hat{P}[\phi_k \otimes \xi_k].$$

Let us now turn to the partial trace technique. In the open-systems approach, a third system, the environment (which may be a part of the measuring apparatus containing many degrees of freedom), is included and then traced out in order to induce classical behavior on the composite system. The use of the partial trace starts by a unitary evolution involving object, apparatus, and environment, represented by $\hat{U}_2$. The states $|\varepsilon_i\rangle$ form an orthonormal basis spanning the Hilbert space $\mathbf{H_e}$ representing the environment:

$$(10) \qquad \left|\sum_i a_i \cdot \phi_i\right\rangle \otimes |\xi_0\rangle \otimes |\varepsilon_0\rangle \xrightarrow{\hat{U}_2} \left|\sum_i a_i \cdot \phi_i \otimes \xi_i \otimes \varepsilon_i\right\rangle.$$

The evolution operator $\hat{U}_2$ is of a very special form. If only two subsystems were involved, no restriction would have to be imposed on the evolution operator leading from an initially uncorrelated state to the state of Equation (3), because of Schmidt’s theorem (this case would correspond to a generalized version of Equation (7)). In the case of three subsystems, however, there are states that cannot be represented by the right-hand side of Equation (10), even if the orthonormal bases be chosen at will. The evolution operator $\hat{U}_2$ must therefore be of a very special form in order to satisfy Equation (10). This limitation is not explicitly stated in Zurek's 1991 review article (see his Equation (7)), although he has previously stressed that the interaction Hamiltonian is of a special form (Zurek 1981, pp. 1520–1521; Zurek 1982, p. 1865).

Now the partial trace may be performed (Equation (5)), eliminating the unobserved environmental states:

$$(11) \qquad \sum_k \langle \varepsilon_k | \hat{P} \left[\sum_i a_i \cdot \phi_i \otimes \xi_i \otimes \varepsilon_i \right] | \varepsilon_k \rangle = \sum_k |a_k|^2 \cdot \hat{P}[\phi_k \otimes \xi_k],$$

the right-hand side of which is identical to that of Equation (9), obtained by applying the projection postulate in the statistical case. As mentioned before, the partial trace approach cannot handle the individual case, analogous to Equation (8).

One advantage of the approach involving partial trace (Zurek 1982, pp. 1867, 1871) is that the apparatus pointer states $|\xi_i\rangle$ arise naturally from the formalism. In other words, the 'pointer observable' being 'measured' or 'monitored' by the environment arises naturally from the unitary operator $\hat{U}_2$ indicated in Equation (10), or equivalently, from the interaction Hamiltonian. A change in the interaction Hamiltonian (still satisfying Equation (10) for a different evolution operator $\hat{U}_2'$) will lead to a different observable being measured. The decoherence approach may thus conclude that the classical behaving set of apparatus states arises from the interaction with a large environment, which induces 'superselection rules' on the apparatus system.

The traditional approach which relies on the projection postulate must define a priori the apparatus pointer states which do not superpose, and these, together with the unitary evolution operator $\hat{U}_1$ of Equation (7), define the observable being measured. The decoherence approach, in contrast, has the explanatory advantage of only having to define $\hat{U}_2$.

In spite of this advantage, the fact (mentioned above) that this evolution operator has to be of a special restricted form constitutes, in our opinion, a serious drawback for the decoherence approach to the quantum theory of measurement. There is no experimental evidence that the interaction between apparatuses and environments satisfies Equation (10). What would happen if the evolution operator for a three-part system violated Equation (10)?

For a more general unitary evolution operator $\hat{U}_3$, we would have:

$$\text{(12)} \qquad \left| \sum_i a_i \cdot \phi_i \right\rangle \otimes |\xi_0\rangle \otimes |\varepsilon_0\rangle \xrightarrow{\hat{U}_3} \left| \sum_i a_i \cdot \zeta_i \otimes \varepsilon_i \right\rangle,$$

where each of the composite states $|\zeta_i\rangle$, which form an orthonormal set, *cannot*, in general, be expressed as a direct product $|\phi'_i \otimes \xi_i\rangle$ involving some orthonormal set of apparatus states $|\xi_i\rangle$, even if the object states $|\phi'_i\rangle$ do not form an orthonormal set. The tracing of environmental coordinates would furnish $\sum_k |a_k|^2 \cdot \hat{P}[\zeta_k]$, which does not correspond to orthogonal pointer states.

This situation would therefore not count as a measurement interaction. But couldn't it take place? What justification can be given for limiting the interaction $\hat{U}_2$ to the form given in Equation (10)? Our opinion is that the decoherence approach to quantum measurement theory should also work for a more general interaction between the measurement apparatus and the environment, although the theory advanced by Zurek does not.

10. SUBJECTIVISM WITHIN THE DECOHERENCE APPROACH

We have mentioned in Section 5 that the open-systems paradigm suffers from what we called the problem of the closed universe, so that it cannot escape from the restrictions imposed by the insolubility proofs of the completeness problem. In other words, after a measurement is completed, the universe cannot be represented exactly by a diagonal density matrix in the apparatus pointer state basis. The decoherence approach (which shares the open-systems paradigm) has been able to achieve a diagonal density matrix for the apparatus; however, this occurs because the use of the partial trace is equivalent to the application of the projection postulate, as we have argued in Section 8.

Besides the formal similarities between the projection postulate and the partial trace, there are some conceptual similarities between the two. The most important of these conceptual similarities is the *arbitrariness as to where to draw the boundary between quantum and classical.* For a simple object system surrounded by an environment consisting of many subsystems, what justifies tracing out *all* of the environmental coordinates? Why couldn't only part of these coordinates be traced out, in such a way that the object system would be enlarged by that part of the environment that had not been traced out? Is Bell (1990, p. 19) correct in his criticism that 'the concepts "system", "apparatus", "environment", immediately imply an artificial division of the world'? We have quoted Fano's justification in

Section 6, which appeals to our ‘practical interest’ in the object system, and not in the environment; or we can follow von Neumann’s suggestion, and argue that the environment is ‘unobserved’. But unobserved by whom?

The open-systems approach introduced the notion that the environment can ‘measure’ or monitor a quantum system, performing continuous measurements, without requiring the presence of a human observer or even of a measuring apparatus. This constituted a further step towards objectivism, the trend that started in the 1950s (as we mentioned in Section 1) in rejection of subjectivism and idealism in quantum mechanics. However, how are we to justify placing a boundary at a specific point between quantum system and environment? If the application of the partial trace at a certain point is justified by claiming that ‘environmental coordinates are not observed or are not of interest’, an element of subjectivism is reintroduced into our picture of the quantum world. Are we forced to say that the system only loses coherence when we choose what to observe and what not to observe? Can the decoherence approach be reconciled with objectivity?

Zeh (1971, p. 272) has acknowledged this element of subjectivity in ‘the arbitrariness of the separation of the universe into two subsystems’. In recent work, Zurek (1993, p. 288) has also explicitly considered the charge that the decoherence approach is subjective or even ‘anthropocentric’. He defends, however, the objectivity of his view by remarking that his theory only deals with unitary evolutions (of the global system). What he seems to be saying is that taking a partial trace is not essential for the existence of classical behaviour, being only a technique for *identifying* situations of ‘emerging classicality’.

This realist position sounds reasonable. It implies, however, that *the justification for taking a partial trace has nothing to do with the fact that environmental coordinates are unobserved or of no practical interest.* The partial trace can be used to eliminate the coordinates of *any* subsystem of the global system. Taking a partial trace, obtaining a reduced density operator $\hat{W}$, and computing $\mathrm{Tr}(\hat{W}^2)$ are part of a procedure for checking “how classical” the behavior of any subsystem is. The choice of where to draw the boundary between object and environment is independent of where the “real” boundary between classical and quantum might be (*if* such a “real” boundary exists at all: a detailed theory of how to distinguish between classical and quantum domains is still an open problem).

11. COLLAPSE WITHIN THE DECOHERENCE APPROACH

In the previous section we examined the charge of subjectivity related to the arbitrariness of the boundary between system and environment. A different type of subjectivity arises in the treatment given by Zeh and by Zurek to the collapse of the state vector.

Recall the distinction made in Section 2 between decoherence and collapse. The explanation given for statistical decoherence does not suffice for explaining collapse of an individual system. Granted this, how do the defenders of the decoherence approach try to account for state collapse?

Zeh (1970, 1993) never considered that the measurement problem for individual systems (the problem of state collapse) could be solved simply by tracing out environmental coordinates. He therefore appealed to Everett's (1957) 'relative state' formulation of quantum mechanics. According to this interpretation, collapses don't really occur from the point of view of the universe as a whole, which is closed. What happens is that memory states in the scientist's brain get correlated with quantum 'pointer states', and each of these memory states doesn't have access to other memory states orthogonal to it. This position, considered 'extravagant' by many, reintroduces the observer into the picture, and in this sense might be considered a retreat to subjectivity.

In contrast to Zeh, Zurek has been more ambiguous on this issue. At first he explicitly admonished that 'we do not face the insoluble question of quantum theory of measurement: "what causes the collapse of the system-apparatus-environment combined wave function?" ' (Zurek 1981, p. 1517). However, he later declared that the decoherence interpretation could explain 'how the interaction of the apparatus and the environment can cause an effective reduction of the state vector' (Zurek 1982, p. 1866). 'We have invoked environment, and the transfer of information from the apparatus-system object to the environment-apparatus correlations as the ultimate cause of the apparent wave packet collapse' (p. 1877). According to his view, the information contained in a pure state is not decreased during environmental monitoring (or during measurement), but 'in the case of a large environment it becomes "dissolved" in all the available degrees of freedom [. . .]' (p. 1874). 'The environment acts as a higher-order apparatus, which performs nondemolition measurement on the state of the system [. . .]' (p. 1870).

The impression passed by Zurek was that environmentally-induced decoherence could be the key for solving the measurement problem, even in the individual case. This suggestion was attractive, furnishing a nice intuitive picture for state collapse: the universe would be described by a pure state vector, and the "coherence" initially present in the quantum object would spread out into the environment and be conserved. Poincaré recurrences would still occur for finite environments, so that a system which underwent state collapse could recover its initial pure state, but the time span for such an occurence would be longer than the age of the universe. State collapse and the projection postulate, for the individual case, seemed to be explained, at least in an approximate way, for all practical purposes.

A decade later, however, Zurek (1993) would clearly distinguish decoherence from collapse. In order to explain state collapse within the decoherence approach, Zurek followed Zeh in appealing to Everett's relative state interpretation. Collapse would correspond to a modification in the observer's brain state occurring during the timescale of decoherence (Zurek 1993, p. 311).

This incorporation of the observer's quantum state into the picture can be considered a form of subjectivism. Everett's solution to the measurement problem is logically consistent and empirically adequate, but it is philosophically unsatisfactory within the tradition of objectivism in quantum mechanics. This consideration has been used by Ghirardi *et al.* (1987) to criticize the decoherence approach, in a debate with Joos (1987).

Our reasons for rejecting Everett's views is not only that it is philosophically extravagant: the issue is that there seems to be strong evidence that quantum coherence cannot be amplified in usual experimental setups. When the scientist observes a measurement outcome, or when an apparatus pointer responds to a microscopic current, the situation is already classical, individual pointers are already in well-defined positions and not in superpositions. Amplification (as it is currently done in laboratories) seems to be a sufficient condition not only for decoherence but also for state collapse (although not a necessary one, as we have mentioned in Section 4). Schrödinger's cat never exists in a superposition of living and dead states, because collapse already happens during amplification of the microscopic signal. That is not to say, however, that macroscopic superpositions are impossible: the consensus seems to be that such superpositions will eventually be observed, the day technology allows the interaction with the environment to be shielded, and the decoherence time to be greater that the observation time (for recent experiments on this issue, see Davidovich *et al.* 1996).

This last remark reminds us again of the situation described in Section 2: the decoherence approach is able to explain why a system does *not* collapse (its decoherence time is long), but it does not explain why a system does collapse. A system that decoheres is described by a classically behaving mixture, but to describe state collapse for a single system one has also to consider the pure state underlying the mixture.

The program we advance in the next section is that of constructing a theory in which decoherence is a necessary *and sufficient* condition for collapse. How could this be done?

12. ENVIRONMENTALLY-INDUCED COLLAPSE: A PROGRAM

The initial hopes of using environmental monitoring to explain individual state collapse, besides explaining the selection of a pointer basis, has been clearly abandoned by Zurek. However, the project of accounting for state collapse by means of a large interacting environment was originally very promising. One would be able to consider state collapse as a physical process occuring independently of an observer or even of a measuring apparatus. The continuous dissipation of coherence throughout the environment fits in well with the idea that state collapse should be a continuous process.

What happens when a single quantum system decoheres? If one adopts the 'ignorance interpretation' of mixtures (see for instance Pessoa 1992), one considers that a single system represented by a proper mixture is in fact in a well-defined but unknown pure state. How about a single system represented by an improper mixture (reduced density matrix)? In this case there is no underlying pure state for the object system alone, because the system is entangled with the environmental system, although there is a composite (object plus environment) pure state. However, after a single system is measured it does collapse to a pure pointer state, possibly an unknown one. For an ensemble, then, the final state after the measurement is a proper mixture (assuming, still, the ignorance interpretation). How does the improper mixture become a proper one? If the environment does effectively induce a collapse, how does the pure composite state evolve into the collapsed object state? The decoherence approach, based on the partial trace, has no tools to answer this question.

The problem of describing individual collapses has been addressed within an important rival research program to the decoherence paradigm, the 'spontaneous localization' approach (Ghirardi *et al.* 1986; Ghirardi *et al.* 1990; Gisin and Percival 1992), which introduces stochastic collapses of the state vector. The state vector is treated as a real entity which undergoes spontaneous collapses with a very low probability for single particles, but which for a macroscopic number of particles becomes quite high.

Our suggestion here is that the decoherence program can incorporate certain insights of the spontaneous localization program, in order to account for the decoherence of a single system. Two points should be adopted.

First, one should 'suppose the state vector is real' (Pearle 1986), in spite of it being defined in high dimensional Hilbert spaces. This thesis characterizes the wave (or polywave) interpretation of quantum mechanics, defended by Schrödinger and implicit in Everett's view, and which denies the existence of particles. Within the decoherence approach, Zeh (1993) has adopted this interpretation, as he explicitly announced that 'there are no quantum jumps, nor are there particles'. Zurek, in contrast, places himself very close to the consistent histories interpretation of quantum mechanics, which is usually considered an improved version of the orthodox interpretation.

The second insight to be adopted from the spontaneous localization program is that the final state after collapse is chosen *at random*. But what is the difference between the extended decoherence approach suggested here and the stochastic localizations theory? The difference is that, in our view, the stochastic collapses should not occur spontaneously, but should be caused by the random encounters with particles in the environment, which would carry away coherence. This would maintain cryptodeterminism (Section 4) and maintain the 'hard core' of the decoherence program. The suggestion is therefore that a quantum system has interactions or collisions with other systems which are randomly located in the environment, and these microscopic fluctuations determine somehow the (more or less) continuous collapse of the state vector. The decoherence approach, as it now stands, would be a thermodynamical point of view, which averages out the microscopic fluctuations. But to attempt an explanation for state collapse one must take into account such fluctuations.

The problem to be attacked is to describe the passage of a quantum object from a initial pure superposition to a final pure eigenstate in a more or less continuous way, admitting that in between the system cannot be adequately described as a pure state. Of course, the solution of this problem would amount to a solution of the characterization problem, which has been shown to be insoluble (Section 4). But, within the open-systems paradigm, the strategy is to admit an approximate solution, involving the coupling of the object to the environment, and the 'dissolution' of the object's coherence within the environment. This program has been developed at the level of statistical ensembles (the decoherence approach). Our proposal is that it be somehow extended to the level of individual object systems.[6]

13. CONCLUSION

After presenting an overview of the measurement problem and of the attractive features of the open-systems paradigm (Sections 1–7), we have criticized certain theses associated with the decoherence approach. We have stressed that taking a partial trace is equivalent to the statistical version of the projection postulate (Section 8). We have questioned Zurek's theory of measurement, because of the ad hoc limitations he must impose on the interaction between object, apparatus and environment (Section 9).

We have also rejected the incorporation of Everett's branching of memory records into the decoherence program (Section 11).

Having made such negative criticisms to the decoherence approach, we were able to give at least one additional positive assessment of this view: the decoherence approach does not lead to subjectivism, since the boundary between object system and environment can be placed anywhere (Section 10), and the branching of memory records can be rejected.

Finally, in Section 12, we have revealed our sympathy for the open-systems paradigm, and suggested that the interaction with the environment should account not only for statistical decoherence, but also for collapse of an individual system.

So, to answer the question posed by the title of this paper, we may start by saying that the decoherence approach furnishes only an approximate solution to the statistical version of the measurement problem. However, it clearly does not solve the problem of collapse for individual systems, as Zeh, Zurek, and others have noted. But could the decoherence approach *help* to solve the measurement problem, that is, could the open-systems paradigm furnish key ideas for solving the problem for individual systems? Our hopes are that it can, at least in the approximate way mentioned above, as long as the transfer of coherence to the environment be adequately described at the level of state vectors.

NOTES

[*] This paper arose from discussions with Carlos Escobar, Léa Santos and Paulo Marques. Financial support for the research was provided by the National Research Council of Brazil (CNPq). Travel expenses to the 10th Int'l Congress of Logic, Methodology and Philosophy of Science, where these ideas were presented, were provided by the State of São Paulo Foundation for the Support of Research (FAPESP).

[1] This distinction between collapse and decoherence might not be relevant in the statistical ensemble interpretation of quantum mechanics, for which a state vector describes an ensemble of identically prepared systems, and not an individual system in a complete way. The question of what occurs at the individual level when decoherence takes place does not make much sense within a instrumentalistic view of mixtures (which is usually shared by proponents of the ensemble interpretation), and can only be formulated in the so-called ignorance view of mixtures (see Pessoa 1992). This might explain why so many authors have not distinguished between decoherence and collapse.

[2] There has been an interesting proposal by Scully and co-workers to explain decoherence simply by means of an entanglement of the object system with few degrees of freedom in the environment (i.e., apparatus). Contrary to their claim, however, it is not clear that decoherence can occur without the introduction of a disturbance (leading to random phases). See discussion in Englert *et al*. 1995.

[3] See review of the insolubility proofs by Brown (1986). The proofs have not yet been extended to positive operator-valued measurements (see Pessoa 1994).

[4] Caldeira and Leggett (1983) assumed that the spectral density $I(\omega)$ for the continuuum of harmonic oscillators of the environment is "ohmic": $I(\omega) = \eta\omega$, with a certain cutoff frequency. They also assumed that the interaction between the object system, taken to be a harmonic oscillator with position x, and each of the environmental oscillators with position r_i, is linear: $\hat{H}_{\text{int.}} = \hat{x} \sum_i c_i \cdot \hat{r}_i$. They also worked in the high temperature limit $(kT \gg \hbar\omega_i)$, assuming as initial conditions that that object and environment are uncorrelated, and that the environment is in thermal equilibrium. The ohmic, linear interaction, and high temperature conditions have been dropped by other researchers, who obtained more complicated expressions for the generalized Master equations (see Hu *et al*. 1992–93).

[5] The first use of the technique of partial trace in attempting to solve the measurement problem was probably that of Jauch (1964, pp. 311–314). He divided the apparatus into a microscopic part and a macroscopic amplifier. First, the object system and the microscopic part of the apparatus interact unitarily. Then, since the amplifier is only coupled to the microscopic apparatus and not to the object system, one would be justified in tracing out the object states, obtaining a reduced mixture for the microscopic apparatus alone. The amplifier would 'see' the microscopic part as a reduced density operator, and that would be equivalent to applying the projection postulate. Jauch then argued that the pure composite state that evolves during measurement would be indistinguishable from the mixture that arises from the projection postulate (see d'Espagnat 1976, pp. 173–185). It is curious that in using the partial trace Jauch traced out the object quantum states, while the usual approach is to trace out the environmental states.

[6] Within the stochastic localization approach, Gisin and Percival (1992) have come closest to implementing the program suggested in this paper, representing the interaction of an individual system with the environment by means of nonlinear stochastic diffusion equations. From another point of view, Hans Primas (1990), from Zurich, has developed in some detail an approach based on algebraic quantum mechanics which emphasizes that 'a theory of open systems should be based on an individual description', a project also developed by his colleague W. Zaoral (1991).

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