Decoherence, measurement and interpretation of quantum mechanics

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According to our modal-Hamiltonian interpretation (MHI) of quantum mechanics, the Hamiltonian of the closed system defines the set of its definite-valued observables. This definition seems to be incompatible with the pointer basis selected by the environment-induced decoherence (EID) of the open system. In this paper we argue that decoherence can be understood from a closed system perspective which (i) shows that the incompatibility between MHI and EID is only apparent, and (ii) solves certain conceptual challenges that the EID program still has to face.

I. INTRODUCTION

Since the early days of quantum mechanics, the measurement problem has been one of the most serious challenges for the interpretation of the theory, and much ink has been spilled over the search of an adequate solution. During the last decades, environment-induced decoherence (EID) has become an unavoidable element in the explanation of quantum measurement ([1], [2]). The core of the decoherence program relies on the interaction between the measuring apparatus and its environment: the continuous “monitoring” of the environment leads interference to vanish with respect to a definite preferred basis, which turns out to be the eigenbasis of the pointer observable of the measuring apparatus. According to Schlosshauer ([3], p.1287; see also [4]), “based on the progress already achieved by the decoherence program, it is reasonable to anticipate that decoherence embedded in some additional interpretive structure could lead to a complete and consistent derivation of the classical world from quantum-mechanical principles.”

Recently we have proposed a new interpretation of quantum mechanics ([5], [6], [7], [8]), belonging to the “modal family”: like previous modal interpretations, our modal-Hamiltonian interpretation (MHI) is a realist, non-collapse approach, according to which the quantum state describes the possible properties of the system but not its actual properties (see [9]). Then, any modal interpretation is committed to state a rule that selects the preferred context, that is, the set of the actually definite-valued observables of the quantum system. According to the MHI, the preferred context is defined by the Hamiltonian of the system, which is conceived as a closed system with no external interaction. To the extent that EID applies to open systems, this seems to mean that the MHI cannot supply the interpretive structure that would allow decoherence to offer an adequate account of the classical limit of quantum mechanics. Given the great success of the EID program, this would count against the acceptability of the MHI.

The aim of this paper is to show that the conflict between EID and MHI is merely apparent, and only due to the open-system perspective from which the theory of decoherence is usually presented. However, decoherence can be explained from a closed-system perspective, in terms of which the seeming conflict vanishes. Moreover, from a general viewpoint we will argue that this closed-system approach solves certain conceptual challenges that the EID program still has to face.

II. THE MEASUREMENT PROBLEM

In the standard von Neumann model, a quantum measurement is conceived as an interaction between a system $S$ and a measuring apparatus $M$. Before the interaction, $M$ is prepared in a ready-to-measure state $|p_0\rangle$, eigenvector of the pointer observable $P$ of $M$, and the state $|\psi_0\rangle$ of $S$ is a superposition of the eigenstates $|a_i\rangle$ of an observable $A$ of $S$. The interaction introduces a correlation between the eigenstates $|a_i\rangle$ of $A$ and the eigenstates $|p_i\rangle$ of $P$:

$$|\psi_0\rangle = \sum_i c_i |a_i\rangle \otimes |p_0\rangle \longrightarrow |\psi\rangle = \sum_i c_i |a_i\rangle \otimes |p_i\rangle$$  \hspace{1cm} (1)

The problem consists in explaining why, being the state $|\psi\rangle$ a superposition of the $|a_i\rangle \otimes |p_i\rangle$, the pointer $P$ acquires a definite value.

In the orthodox collapse interpretation, the pure state $|\psi\rangle$ is assumed to “collapse” to a mixture $\rho^c$:

$$\rho^c = \sum_i |c_i|^2 |a_i\rangle \otimes |p_i\rangle \langle a_i| \otimes \langle p_i|$$  \hspace{1cm} (2)
where the probabilities $|c_i|^2$ are given an ignorance interpretation. Then, in this situation it is supposed that the measuring apparatus is in one of the eigenvectors $|p_i\rangle$ of $P$, say $|p_k\rangle$, and therefore $P$ acquires a definite value $p_k$, the eigenvalue corresponding to the eigenvector $|p_k\rangle$, with probability $|c_k|^2$. In the modal interpretations, the problem is to explain the definite reading of the pointer, with its associated probability, without assuming the collapse hypothesis.

III. THE MHI ACCOUNT OF MEASUREMENT

In order to study the physical world, we have to identify the systems that populate it. By adopting an algebraic perspective, the MHI defines a quantum system $S$ as a pair $(O, H)$ such that (i) $O$ is a space of self-adjoint operators on a Hilbert space $\mathcal{H}$, representing the observables of the system, (ii) $H \in \mathcal{O}$ is the time-independent Hamiltonian of the system, and (iii) if $\rho_0 \in \mathcal{O}'$ (where $\mathcal{O}'$ is the dual space of $\mathcal{O}$) is the initial state of $S$, $\rho_0$ evolves according to the Schrödinger equation in its von Neumann version.

Of course, any quantum system can be decomposed in parts in many ways; however, not any decomposition will lead to parts which are, in turn, quantum systems. According to the MHI, a quantum system $S : (O, H)$ with initial state $\rho_0 \in \mathcal{O}'$ is composite when it can be partitioned into two quantum systems $S_1 : (O_1, H_1)$ and $S_2 : (O_2, H_2)$ such that (i) $O = O_1 \otimes O_2$, and (ii) $H = H_1 \otimes I_2 + I_1 \otimes H_2$ (where $I_1$ and $I_2$ are the identity operators in the corresponding tensor product spaces). In this case, the initial states of $S_1$ and $S_2$ are obtained as the partial traces $\rho_{01} = Tr_2(\rho_0)$ and $\rho_{02} = Tr_1(\rho_0)$, and we say that $S_1$ and $S_2$ are subsystems of the composite system $S$.

If the quantum system is not composite, we call it elemental. There are different, equally legitimate ways of decomposing an elemental system $S : (O, H)$ with initial state $\rho_0 \in \mathcal{O}'$ into “parts” $P_1 : (O_1, H_1)$ and $P_2 : (O_2, H_2)$, with initial states $\rho_{01} \in \mathcal{O}'_1$ and $\rho_{02} \in \mathcal{O}'_2$, respectively, such that (i) $O = O_1 \otimes O_2$, (ii) $H = H_1 \otimes I_2 + I_1 \otimes H_2 + H_{12}^{int}$, where $H_{12}^{int}$ is the interaction Hamiltonian, and (iii) $\rho_{01} = Tr_2(\rho_0)$ and $\rho_{02} = Tr_1(\rho_0)$ (see [10], [11]). Since $H_{12}^{int} \neq 0$, $\rho_{01}$ and $\rho_{02}$ do not evolve unitarily according to the Schrödinger equation: it is for this reason that $P_1$ and $P_2$ are not subsystems but have to be considered as mere parts of $S$.

Given the contextuality of quantum mechanics, the subtler point in any realist interpretation is the selection of the preferred context. In the MHI this selection is based on the actualization rule, which defines, among all the observables of the system, those that acquire actual, and not merely possible definite values. The basic idea is that the Hamiltonian of the system defines actualization; therefore, any observable that does not have the symmetries of the Hamiltonian cannot acquire an actual value, since its actualization would break the symmetry of the system in an arbitrary way. Precisely, the MHI actualization rule states that, given an elemental quantum system $S : (O, H)$, the preferred context consists of $H$ and the observables commuting with $H$ and having, at least, the same symmetries as $H$. This rule has been applied to many well-known physical situations (hydrogen atom, Zeeman effect, fine structure, etc.), leading to results consistent with experimental evidence (see [2], [6]). Moreover, it has proved to be effective for solving the measurement problem, both in its ideal and its non-ideal versions; for our purposes, we will only focalize on measurement.

According to the MHI, a quantum measurement is a three-stage process. In the first stage, the system $S$ to be measured is represented in the Hilbert space $\mathcal{H}_S$ and with Hamiltonian $H_S$—and the measuring device $D$—represented in the Hilbert space $\mathcal{H}_D$ and with Hamiltonian $H_D$—do not interact. During the second stage, an interaction Hamiltonian $H_{SD}^{int}$ introduces the correlation between the eigenstates $|a_i\rangle$ of an observable $A$ of $S$ and the eigenstates $|p_i\rangle$ of a pointer observable $P$ of $D$ (see [12]). In the third stage the interaction ends, and the whole system becomes a composite system $S \cup D$ with a Hamiltonian

$$H = H_S \otimes I_D + I_S \otimes H_D$$ (3)

and an initial state (see eq.11)

$$|\psi_{SD}\rangle = \sum_{i} c_i |a_i\rangle \otimes |p_i\rangle$$ (4)

Although $|\psi_{SD}\rangle$ is an entangled state, since there is no interaction between the subsystems $S$ and $D$, the actualization rule has to be applied to each one of them independently. In particular, when applied to $D$, the rule states that the definite-valued observables are the Hamiltonian $H_D$ and all the observables commuting with $H_D$ and having, at least, the same symmetries—degeneracies— as $H_D$.

Of course, not any quantum process can be considered a quantum measurement. On the basis of the above description, we can formulate the conditions that define a quantum measurement:

(a) During a period $\Delta t$, $S$ and $D$ must interact through an interaction Hamiltonian $H_{SD}^{int} \neq 0$ intended to introduce a correlation between the observable $A$ of $S$ and the pointer $P$ of $D$. The requirement of perfect correlation is
not included as a defining condition of measurement, because the actualization rule explains the definite reading of the pointer \( P \) even in non-ideal measurements, that is, when the correlation is not perfect. In this case, the rule also accounts for the difference between reliable and non-reliable measurements (see \( \text{[4]} \), Section 6).

(b) The measuring device \( D \) has to be such that its pointer \( P \) (i) has macroscopically distinguishable eigenvalues, and (ii) commutes with the Hamiltonian \( H_D \) and has, at least, the same degeneracy as \( H_D \). The condition \( [P, H_D] = 0 \), besides to explain the definite reading of the pointer according to the MHI actualization rule, guarantees the stationarity of the eigenvectors of \( P \), making the readings of the pointer possible.

This account of the quantum measurement has been used to explain how the initial —pure or mixed— state is reconstructed through measurement both in the ideal and in the non-ideal case, and has been successfully applied to the paradigmatic example of the Stern-Gerlach experiment, with perfect and non perfect correlation, and also in the case of an imperfect collimation of the incoming beam (see \( \text{[4]} \), Section 6).

IV. THE EID ACCOUNT OF MEASUREMENT

As it is well-known, the key idea of the decoherence program is that macroscopic systems, like measuring apparatuses, are never isolated but always interact with their environments. In the von Neumann model of measurement (see eq.11), when the environment \( E \) is taken into account, after the correlation the initial state of the whole system \( S + M + E \) becomes

\[
|\psi_{SME}(0)\rangle = \left( \sum_i c_i |a_i\rangle \otimes |p_i\rangle \right) \otimes |e_0\rangle
\]  

where \( |e_0\rangle \) is the state of the environment before its interaction with the measuring apparatus. Zurek and his collaborators prove that, when the interaction Hamiltonian between the measuring apparatus \( M \) and the environment \( E, H_{ME}^{int} \), satisfies certain conditions (see \( \text{[13]} \)), \( |\psi_{SME}(0)\rangle \) evolves into

\[
|\psi_{SME}(t)\rangle = \sum_i c_i |a_i\rangle \otimes |p_i\rangle \otimes |e_i(t)\rangle
\]  

where the \( |e_i(t)\rangle \) are the states of the environment associated with the different pointer states \( |p_i\rangle \). According to Zurek, the state of the system \( S + M \) is represented by the reduced density operator \( \rho_r(t) \) resulting from tracing over the environmental degrees of freedom,

\[
\rho_r(t) = Tr_E (|\psi_{SME}(t)\rangle \langle \psi_{SME}(t)|) = \sum_{ij} c_i^* c_j |a_i\rangle \otimes |p_i\rangle \langle a_j \otimes |p_j\rangle \sum_l \langle e_l(t)|e_i(t)\rangle \langle e_l(t)|e_i(t)\rangle
\]  

where the factor \( r_{ij}(t) = \sum_l \langle e_l(t)|e_i(t)\rangle \langle e_l(t)|e_i(t)\rangle \) determines the size of the off-diagonal terms at each time. Many standard models for the interaction Hamiltonian \( H_{ME}^{int} \) show that, when the environment is composed of a large number of subsystems, the states \( |e_i(t)\rangle \) of the environment rapidly approach orthogonality. This means that the reduced density operator rapidly becomes diagonal in the preferred basis \( \{|a_i\rangle \otimes |p_i\rangle\} \) (compare with eq.(2))

\[
r_{ij}(t) \to \delta_{ij} \quad \Rightarrow \quad \rho_r(t) \to \rho_r = \sum_i |c_i|^2 |a_i\rangle \otimes |p_i\rangle \langle a_i | \otimes \langle p_i|\]
\]  

According to Zurek (13, 1), in a certain sense decoherence “explains” the collapse of the state vector.

In his first papers, Zurek studied physical models where the interaction between the measuring apparatus and the environment dominates the process (13, 14); in those cases, the reduced density matrix ends up being diagonal in the eigenvectors of an observable \( P \) that commutes with the Hamiltonian \( H_{ME}^{int} \) describing the apparatus-environment interaction. This property is what makes \( P \) to be the pointer observable: since \( P \) is a constant of motion of \( H_{ME}^{int} \), when the apparatus is in one of its eigenstates, the interaction with the environment will leave it unperturbed. Since those first works, the condition \( [P, H_{ME}^{int}] = 0 \) has usually be considered as the definition of the pointer basis or of the pointer observable \( P \) of the apparatus (see, for instance, 17, p.363, 3, pp.1278-1279).

In the 90’s, Zurek stressed that the original definition of the pointer basis was a simplification: in more general situations, when the system’s dynamics is relevant, the einselection of the preferred basis is more complicated. Zurek
introduced the “predictability sieve” criterion ([16], [17]) as a systematic strategy to identify the preferred basis in generic situations. The criterion is based on the fact that the preferred states are, by definition, those less affected by the interaction with the environment, in the sense that they are the ones less entangled with it. On the basis of the application of this criterion, three basically different regimes for the selection of the preferred basis can be distinguished ([18], [2]):

- The first regime is the quantum measurement situation, where the self-Hamiltonian of the system can be neglected and the evolution is completely dominated by the interaction Hamiltonian. In such a case, the preferred states are directly the eigenstates of the interaction Hamiltonian ([13]).

- The second regime is the more realistic and complex situation, where neither the self-Hamiltonian of the system nor the interaction with the environment are clearly dominant, but both induce non-trivial evolution. In this case, the preferred basis arises from the interplay between self-evolution and interaction; quantum Brownian motion belongs to this case ([19]).

- The third regime corresponds to the situation where the dynamics is dominated by the system’s self-Hamiltonian. In this case, the preferred states are simply the eigenstates of this self-Hamiltonian ([18]).

According to Schlosshauer ([3], p.1280), these three regimes explain why many systems, specially in the macroscopic domain, are typically found in energy eigenstates, even if the interaction Hamiltonian depends on an observable different than energy.

V. MEASUREMENT FROM A CLOSED-SYSTEM PERSPECTIVE

As we have seen, the actualization rule of the MHI explains the definite reading of the pointer $P$ of the measuring device $D$ by considering that $P$ commutes with the Hamiltonian $H_D$ of $D$ and does not break the degeneracies of such a Hamiltonian. This account of the quantum measurement seems to be at odds with the explanation given by the EID program, according to which the decoherence of the measuring apparatus in interaction with its environment is what causes the apparent “collapse” that suppresses superpositions. In fact, in the MHI, the environment is absent: after the interaction $D$ is a closed quantum system unitarily evolving with its own Hamiltonian $H_D$. Moreover, this seems to flagrantly contradict the fact that real measuring apparatuses are never isolated, but they interact significantly with their environments. However, this apparent conflict vanishes when a “closed-system” perspective is adopted.

A. Revisiting the MHI account of measurement

If measurement is described in terms of the quantum and, therefore, closed systems involved in the process, the measuring device $D$ has to be considered not as an open macroscopic apparatus $A$ (eventually surrounded by a “bath” $B$ of particles in interaction with it), but as the entire quantum system that interacts with the system $S$ in the second stage and remains closed in the third stage: it is this system what has to have a pointer observable commuting with its Hamiltonian $H_D$. On this basis, we can now analyze the elements participating in the process as described in the framework of the MHI:

- The closed system $D$ — e.g., the open macroscopic apparatus $A$ plus the bath of particles $B$ — is certainly a macroscopic system, whose Hamiltonian is the result of the interaction among a huge number of degrees of freedom. Since, in general, symmetries are broken by interactions, the symmetry of a Hamiltonian decreases with the complexity of the system. Then, a macroscopic system having a Hamiltonian with symmetries is a highly exceptional situation: in the generic case, the energy is the only constant of motion of the macroscopic system. As a consequence, in realistic measurement situations, $H_D$ is non-degenerate,

$$H_D |\omega_k\rangle = \omega_k |\omega_k\rangle \quad \text{with} \quad \omega_k \neq \omega_k',$$

and, therefore, $\{|\omega_k\rangle\}$ is a basis of the Hilbert space $\mathcal{H}_D$ of $D$. This means that, when $[P, H_D] = 0$, we can guarantee that $P$ has, at least, the same degeneracies as $H_D$ because $H_D$ is non-degenerate.

- The pointer $P$ cannot have such a huge number of different eigenvalues as $H_D$, because the experimental physicist must be able to discriminate among them (for instance, in the Stern-Gerlach experiment the pointer has three
eigenvalues). This means that $P$ is a “collective” observable of the closed system $D$ (see [20], [21]), that is, a highly degenerate observable that does not “see” the vast majority of the degrees of freedom of $D$:

$$P = \sum_{n} p_n P_n$$

(10)

where the set $\{P_n\}$ of the eigenprojectors of $P$ spans the Hilbert space $\mathcal{H}_D$ of $D$. If we call $N$ the number of eigenprojectors of $P$, and $K$ the dimension of $\mathcal{H}_D$, then it is clear that $K \gg N$. In other words, the eigenprojectors of $P$ introduce a sort of “coarse-graining” onto the Hilbert space $\mathcal{H}_D$. Therefore, if the Hamiltonian $H_D$ is non-degenerate, the condition $[P, H_D] = 0$ implies that $P$ can be expressed in terms of the energy eigenbasis $\{|\omega_k\rangle\}$ as

$$P = \sum_{n} p_n P_n = \sum_{n} p_n \sum_{i_n} |\omega_{i_n}\rangle \langle \omega_{i_n}|$$

(11)

This expression shows that, since $p_n \neq p_n'$, $P$ has much more degeneracies than $H_D$.

- The requirement $[P, H_D] = 0$, far from being an ad hoc condition necessary to apply the MHI actualization rule, has a clear physical meaning: it is essential to preserve the stationary behavior of $P$ during the third stage of the measurement process. If this requirement did not hold because of the uncontrollable interaction among the microscopic degrees of freedom of the macroscopic device or between the macroscopic device and an external “bath”, the reading of $P$ would constantly change and measurement would be impossible. This goal may be achieved by many different technological means; but, in any case, measurement has to be a controlled situation where the reading of a stable pointer can be obtained.

### B. The pointer basis from a closed-system perspective

In the context of EID, during the third stage the measuring apparatus $M$ does no longer interact with the measured system $S$ but interacts with the environment $E$. If we call, as before, $D = M + E$ the whole system that interacts with $S$ in the second stage but remains closed during the third stage, the question is how to identify the open parts of $D$ to be conceived as the measuring apparatus $M$ and as the environment $E$. This is a legitimate question because, as we have pointed out, a whole closed system may be partitioned in many different ways, none of them more “essential” than the others (see [10], [11]).

A natural assumption is to consider the macroscopic, material apparatus $A$ built for measurement as “the measuring apparatus” $M$, and the bath $B$ of the particles scattering off $A$ as “the environment” $E$; then, $D = A + B$ is the closed system resulting from the interaction between $A$ and $B$. From this position, it is supposed that $A$ is the open system that decoheres: the reduced density operator $\rho^A(t)$ of $A$ should converge to a final time-independent $\rho^A_t$, diagonal in the preferred basis of $A$, that is, its Hilbert space $\mathcal{H}_A$, and the pointer $P$ should define such a basis. However, even if apparently “natural”, this is not the best choice for the splitting of $D$, since it does not take into account the environment internal to the device $A$. In fact, being a macroscopic body, $A$ also has a huge number of degrees of freedom, which have to be “coarse-grained” by $P$ if it is to play the role of the pointer. In other words, since the pointer $P$ must have a small number of different eigenvalues to allow the experimenter to discriminate among them, $P$ is a highly degenerate observable on the Hilbert space $\mathcal{H}_A$ of the open macroscopic apparatus $A$ and, as a consequence, it does not define a basis of $\mathcal{H}_A$.

When we recall that the only univocally definable entity is the —closed— quantum system, and that a quantum system can be partitioned in many, equally legitimate manners, the closed system $D$ can be split in a theoretically best founded way in the measurement case. Let us recall that the pointer $P$ is the observable whose eigenvectors became correlated with the eigenvectors of an observable of the measured system during the second stage of the process, and that the interaction in that stage was deliberately designed to introduce such a correlation. So, if we want that during the third stage $P$ really defines a basis, the open “measuring apparatus” $M$ must be the part of $D$ corresponding to the Hilbert space $\mathcal{H}_M$ where the pointer is non-degenerate. If we call $P_M$ the pointer belonging to $\mathcal{H}_M \otimes \mathcal{H}_M$, it reads

$$P_M = \sum_{n} p_n \left| p_n \right\rangle \langle p_n \right|$$

(12)

where $\{|p_n\rangle\}$ is a basis of $\mathcal{H}_M$. Then, the relevant partition is $\mathcal{H}_D = \mathcal{H}_M \otimes \mathcal{H}_E$, where $\mathcal{H}_E$ is the Hilbert space of the “environment” $E$. If $\{|e_n\rangle\}$ is a basis of $\mathcal{H}_E$, the pointer acting on $\mathcal{H}_D$ can be expressed as a highly degenerate
observable:

\[ P = P_M \otimes I_E = \left( \sum_n p_n |p_n\rangle \langle p_n| \right) \otimes \left( \sum_m |e_m\rangle \langle e_m| \right) \]
\[ = \sum_n p_n \sum_m |p_n\rangle \langle e_m| \langle p_n| \langle e_m| = \sum_n p_n P_n \]

(13)

This agrees with the features of \( P \) in the MHI: \( P \) introduces a sort of “coarse-graining” onto the Hilbert space \( \mathcal{H}_D \) (compare eq. (13) with eq. (10)). The many degrees of freedom corresponding to the degeneracies of \( P \) in \( \mathcal{H}_D \) play the role of the “environment” \( E \), composed by the microscopic degrees of freedom of the macroscopic apparatus \( A \) – internal environment – and the degrees of freedom of the bath \( B \) – external environment –.

C. The agreement between EID and MHI

As we have seen, in the first papers on decoherence, the condition \([P, H_{ME}^{int}] = 0\) was considered as the definition of the pointer basis. However, this definition involves several assumptions. In fact, from a closed-system perspective, the entangled state \( |\psi_{SM E}(t)\rangle \) of the whole system actually evolves according to the Schrödinger equation under the action of the total Hamiltonian \( H_{SM E} = H_S + H_M + H_E + H_{SM}^{int} + H_{SE}^{int} + H_{ME}^{int} \). So, first it is considered that the system-environment interaction and the system-apparatus interaction are zero: \( H_{SE}^{int} = 0 \) and \( H_{SM}^{int} = 0 \). This assumption is reasonable on the basis of the design of the measurement arrangement: after a short time, any interaction with the system ends and the subsystem \( M + E \) follows its independent dynamical evolution; for this reason, also the self-Hamiltonian \( H_S \) of the system can be disregarded. Then, the stability of the pointer strictly requires that

\[ [P, H_{ME}] = 0 \]

(14)

where \( H_{ME} \), when expressed in precise terms, reads

\[ H_{ME} = H_M \otimes I_E + I_M \otimes H_E + H_{ME}^{int} \]

(15)

If we recall that the pointer is an observable \( P \) highly degenerate in the – internal and external – degrees of freedom of the environment (see eq. (13)), condition (14) results

\[ [P, H_{ME}] = [P_M \otimes I_E, H_M \otimes I_E + I_M \otimes H_E + H_{ME}^{int}] = 0 \]

(16)

But since always \([P_M \otimes I_E, I_M \otimes H_E] = 0\), then the stability requirement for the pointer observable becomes that it commutes with the Hamiltonian \( H_M \otimes I_E + H_{ME}^{int} \), where the self-Hamiltonian of the environment is not included:

\[ [P, H_M \otimes I_E + H_{ME}^{int}] = 0 \]

(17)

This argument shows that the condition \([P, H_{ME}^{int}] = 0\) introduced in the first papers on decoherence, that is, that the pointer commutes with the interaction Hamiltonian, is a particular case which holds only when the self-Hamiltonian of \( M \) can be disregarded. It is also clear that the three regimes, distinguished by Zurek as the result of the application of the predictability sieve to a number of models (see Section IV), turn out to be the three particular cases of condition (17), and can be redescribed in terms of that condition:

- When \( H_M \otimes I_E \ll H_{ME}^{int} \), the self-Hamiltonian of \( M \) can be neglected, and then \([P, H_{ME}^{int}] = 0\). Therefore, the preferred basis is defined by the interaction Hamiltonian \( H_{ME}^{int} \).
- When \( H_M \otimes I_E \cong H_{ME}^{int} \), neither the self-Hamiltonian of \( M \) nor the interaction with the environment are clearly dominant. In this case, the preferred basis is defined by condition (17).
- When \( H_M \otimes I_E \gg H_{ME}^{int} \), the dynamics is dominated by self-Hamiltonian of \( M \) and, then, \([P, H_M \otimes I_E] = [P_M \otimes I_E, H_M \otimes I_E] = [P_M, H_M] = 0\). Therefore, the preferred states are simply the eigenstates of \( H_M \).

As a consequence, the fact, noted by Schlosshauer (3, p.1280), that many systems are typically found in energy eigenstates although the interaction Hamiltonian depends on an observable different than energy, far from being surprising, necessarily results from the requirement of stability for the preferred basis. But the point we want to stress here is that, when the EID pointer basis is considered from this closed-system viewpoint, it agrees with the
preferred context as defined by the MHI actualization rule: in both cases, the pointer/preferred basis is given by the Hamiltonian of the whole closed system. In fact, the three regimes identified by Zurek and obtained case by case by means of the predictability sieve criterion, turn out to be particular cases of the MHI characterization of the preferred basis: if the preferred states are defined by the eigenstates of the Hamiltonian of the whole system, it is not hard to realize that they will depend on the Hamiltonian’s component which dominates the whole evolution.

Moreover, when the pointer basis is viewed from this closed-system perspective, Zurek’s first regime can be justified on general grounds. According to Zurek, the first regime is the quantum measurement situation, where the self-Hamiltonian of the measuring system $M$ can be neglected and the evolution is completely dominated by the interaction Hamiltonian; this means that $H_M \otimes I_E \ll H_{int}^{ME}$. If the apparatus is now conceived as the part of the closed system $D$ “viewed” by the pointer $P$, and the environment carries over almost all the degrees of freedom of $D$, it seems reasonable to suppose that, in general, the Hamiltonian corresponding to the interaction with that huge number of degrees of freedom is much greater than the self-Hamiltonian of the “small” part defined by the pointer. Therefore, the condition $H_M \otimes I_E \ll H_{int}^{ME}$ leading to the first regime turns out to have a physical justification.

VI. EID FROM A CLOSED-SYSTEM PERSPECTIVE

Zurek considers that the prejudice which seriously delayed the solution of the problem of the transition from quantum to classical is itself rooted in the fact that the role of the “openness” of a quantum system in the emergence of classicality was ignored for a very long time ([1], [2]). However, since the environment may be external or internal, the decoherence program supplies no general criterion for distinguishing between the system and its environment: the partition of the whole closed system is decided case by case, and usually depends on the previous assumption of the observables that will behave classically (for a discussion of this point, see [22]). Zurek recognizes this problem as a shortcoming of his proposal: “In particular, one issue which has been often taken for granted is looming big as a shortcoming of his proposal: "$\log\$ Zurek considers that the prejudice which seriously delayed the solution of the problem of the transition from quantum to classical is itself rooted in the fact that the role of the “openness” of a quantum system in the emergence of classicality was ignored for a very long time ([1], [2]). However, since the environment may be external or internal, the decoherence program supplies no general criterion for distinguishing between the system and its environment: the partition of the whole closed system is decided case by case, and usually depends on the previous assumption of the observables that will behave classically (for a discussion of this point, see [22]). Zurek recognizes this problem as a shortcoming of his proposal: “In particular, one issue which has been often taken for granted is looming big as a shortcoming of his proposal: "$\log\$ Zurek considers that the prejudice which seriously delayed the solution of the problem of the transition from quantum to classical is itself rooted in the fact that the role of the “openness” of a quantum system in the emergence of classicality was ignored for a very long time ([1], [2]). However, since the environment may be external or internal, the decoherence program supplies no general criterion for distinguishing between the system and its environment: the partition of the whole closed system is decided case by case, and usually depends on the previous assumption of the observables that will behave classically (for a discussion of this point, see [22]). Zurek recognizes this problem as a shortcoming of his proposal: “In particular, one issue which has been often taken for granted is looming big as a shortcoming of his proposal: "$\log\$
decoherence times [29] and have treated a generalization of the spin-bath model (30). But the point to stress here is that, in this closed-system context, the identification of the system of interest and its environment is just a way of selecting the relevant observables of the whole closed system. Since there are many different sets of relevant observables depending on the observational viewpoint adopted, the same closed system can be decomposed in many different ways: each decomposition represents a decision about which degrees of freedom are relevant and which can be disregarded in any case. Since there is no privileged or “essential” decomposition, there is no need of an unequivocal criterion to decide where to place the cut between “the” system and “the” environment. Therefore, the “looming big” problem of defining the systems involved in decoherence is not as serious as Zurek himself supposes: decoherence is relative to the relevant observables selected in each particular case.

VII. CONCLUSIONS

At present it is quite clear that the theory of decoherence does not supply an interpretation of quantum mechanics. Nevertheless, given its impressive empirical success, it is also clear that nowadays no interpretation can ignore the results coming from the EID approach. Our MHI has been successfully applied to many well-known physical situations, and has proved to be effective for solving the measurement problem, both in its ideal and its non-ideal versions. However, since the actualization rule applies to closed systems, the MHI seems to stand at odds of EID.

In this paper we have shown that this assumption is misguided. On the contrary, when the measurement process is viewed from a closed-system perspective, the MHI and the EID accounts of measurement agree: the classical-like states einselected by the interaction with the environment (the eigenvectors of the pointer, elements of the pointer basis) are the eigenvectors of an actual-valued observable belonging to the preferred context according to the MHI. Moreover, we have argued that, ironically, the “looming big” problem of defining the systems involved in decoherence is the consequence of what has been considered to be the main advantage of the decoherence program: its “open-system” perspective. Therefore, the closed-system approach also solves this seeming difficulty, by showing that decoherence is a relative phenomenon that depends on the partition of the closed system that is selected in each particular case.

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