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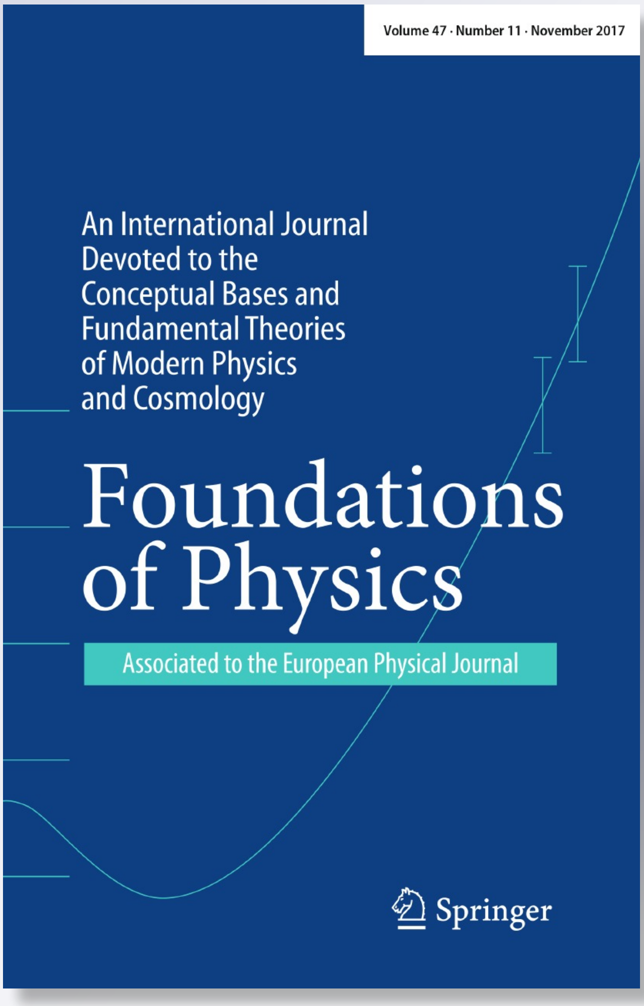

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LETTER TO THE EDITOR

Interpretation and Decoherence: A Contribution to the Debate Vassallo & Esfeld Versus Crull

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To the Editor,

Two recent papers appeared in FOOP disagree regarding the role played by decoherence in quantum physics. On the one hand, Crull [1] considers that decoherence, by itself, solves many conceptual problems in quantum physics, with no need of interpretative considerations. On the other hand, Vassallo and Esfeld [2] reply by correctly claiming that, although decoherence is a powerful tool to deal with conceptual problems, it does not dispense us from interpreting the formalism. In this brief note we want to contribute to the debate with further considerations from another viewpoint.

Vassallo and Esfeld stress the fact that, since in a standard Schrödinger's cat measurement the state of the whole system remains in superposition, the assumption that decoherence solves the measurement problem requires the assumption, among others, that the cat is a quantum system completely described by its own individual state. In fact, this assumption is not irrelevant at all, but brings to the fore the issue of how open systems are conceived. In particular, it requires to reconsider the status of the reduced states that describe their behavior.

In classical statistical mechanics, the standard answer to the irreversibility problem in the Gibbsian framework relies on coarse-graining: whereas the statistical state of the system, represented by a density function, evolves obeying the Liouville theorem, the evolution of coarse-grained states is not constrained by the theorem and, under definite conditions of instability, may approach a definite limit for $t \to \infty$. Of course, there are deep disagreements about the interpretation of the so-obtained irreversibility. But, independently of such disagreements, nobody ignores the difference between the statistical state, which evolves according to the dynamical postulate of the theory,

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and the coarse-grained state, which may tend to a final stable state. The situation in quantum mechanics is quite different: the distinction between the different kinds of states appearing in the quantum discourse is usually not sufficiently emphasized. For instance, sometimes it is said that the dynamical postulate of quantum mechanics only applies to closed systems, whereas reduced operators actually represent quantum states of open systems that evolve according to a different, non-unitary dynamical law. Although it is admitted that reduced states may cancel quantum correlations and, as a consequence, cannot be used for computations in certain cases, the states of closed and open systems are usually treated on equal footing.

In a previous article [3] we have proved that a reduced state provides a description that can be understood by means of a generalized conception of coarse-graining: from being originally conceived as the *quantum state of the open system*, it turns out to be a *coarse-grained state of the closed system*. When the reduced state is viewed as a coarse-grained state, its non-unitary evolution does not restrict the application of the dynamical postulate nor require a new dynamical postulate: it turns out to be an analogous situation to the familiar case of classical instability, where it is completely natural to obtain irreversible coarse-grained evolutions from the underlying reversible dynamics of the unstable system, with no need of restrictions or reformulations of the classical dynamical laws (see, e.g., [4]). An author who has emphasized the analogy between the classical statistical case and the quantum case is Omnès [5,6], who has repeatedly claimed that decoherence is a particular case of the phenomenon of irreversibility. The claim can be endowed with a more precise meaning: as in the case of classical instability, where the coarse-grained state approaches a final state in spite of the reversible evolution of the statistical state, in environment-induced decoherence the reduced state approaches a diagonal reduced state, in spite of the fact that the quantum state indefinitely follows its unitary evolution.

If matters related to the interpretation of the reduced state are conceptually relevant when taken by themselves, they acquire a particular significance in the context of the theory of decoherence. The need of interpreting the phenomenon of decoherence is usually stressed by pointing out that the whole closed system is still in a superposition in spite of the non-unitary evolution of the open system. However, the theory of decoherence, taken by itself, faces some specific challenges that must be seriously considered if one wants to offer a self-consistent view of the emergence of classicality based on decoherence (for discussion, see [7]):

(a) *The closed-system problem*: *the theory of decoherence cannot be applied to closed systems, in particular to the universe as a whole*. The aim of the program "is to describe the consequences of the 'openness' of quantum systems to their environments and to study the emergence of the effective classicality of some of the quantum states and of the associated observables" ([8, p. 1793]; for a different perspective, see [9]). If decoherence explains the emergence of classicality, but only open systems can decohere, the question is: what about closed systems, in particular, the universe as a whole? In the literature, several models can be found that describe decoherence in systems with no environment understood in the traditional way. For instance:

- In the Casati–Prosen model [10,11], decoherence is manifested by the vanishing of the interference pattern on a screen located in a closed cavity. Independently of the details of the model, this is a case in which it is not possible to consider that the phenomenon is due to the interaction with an external environment.

- Gambini and collaborators analyze the influence of an extra term in the evolution equation of quantum systems [12–14]. The term responsible for decoherence, which comes from quantum gravity considerations, does not result from the interaction with an environment, but expresses a coarse-graining due to time-uncertainty.
- Some authors describe decoherence in the Heisenberg representation [15,16]. In this formalism the loss of coherence, treated by means of the Bogoliubov transformation, is due to the dynamics of the system itself.

(b) *The defining-system problem: the theory of decoherence does not provide a univocal criterion to decide where to place the "cut" between the proper system and the environment*. In fact, in the case of closed systems, "internal environments" are defined: the closed system is partitioned into some degrees of freedom representing the system of interest, and the remaining degrees of freedom that play the role of the environment. For example, in the cosmological context, long wavelength modes are usually considered the system, and short wavelength modes are conceived as the environment [17]. However, this is not the only way of introducing the split into the closed system. In a more recent study of the fluctuations generated in the inflationary period of the cosmic evolution, it is supposed that the tensor and scalar fluctuations interact with each other, and tensor fluctuations act as an environment that causes the loss of coherence of the scalar fluctuations, whose classicality is so justified [18]. This cosmological case is only an example of the fact that, although the theory of decoherence studies the correlations between system and environment and also between different subsystems [19], the approach does not supply a general criterion to discriminate between system and environment. In general, the classically-behaving degrees of freedom are assumed in advance: the application of the formalism does not predict which observables will show a classical behavior but only confirms a previous assumption. This problem is acknowledged by Zurek himself: "one issue which has been often taken for granted is looming big, as a foundation of the whole decoherence program. It is the question of what are the "systems" which play such a crucial role in all the discussions of the emergent classicality. This issue was raised earlier, but the progress to date has been slow at best. Moreover, replacing "systems" with, say, "coarse grainings" does not seem to help at all, we have at least tangible evidence of the objectivity of the existence of systems, while coarse-grainings are completely "in the eye of the observer"" ([20, p. 338]; see also [8]).

(c) *The problem of the emergence of the classical world: under certain conditions, the theory of decoherence cannot define a unique classical system emerging from the quantum domain*. If decoherence explains the transition from quantum to classical [21], the emergent classical world must be objective like decoherence itself: it should not be confined to "the eye of the observer". However, as indicated above, the theory does not provide a univocal criterion to distinguish the system of interest from its environment; thereby, the decomposition between system and environment can be introduced in many different ways. In particular, it may happen that, given a decomposition of the closed systems into subsystems, several subsystems decohere but their union does not; therefore, the classicality emerging from the underlying quantum domain is not univocally determined. A concrete example of this case is proposed in [22] (see discussion in [23]): a generalized spin-bath model of $m + n$ spin-1/2 particles, where each particle of the m group interacts with all the particles of the n group and vice versa, but the particles of the m group do not interact with each other and neither do the particles of the n group. The study of the model shows that there are definite conditions under which all the particles decohere, but neither the system composed of the m group nor the system composed of the n group decohere. This means that whereas all the $m+n$ particles may become classical when considered independently, both the system composed of the m group and the system composed of the n group retain their quantum character. This kind of cases poses a conceptual challenge to the decoherence program: if classicality is conceived as an objective property, the fact that a system behaves classically or not should not depend on the way in which the observer decides to split the original closed system. In other words, this situation calls into question the spirit of the original proposal, according to which decoherence provides the basis of a classic limit that explains the objective emergence of the classical world.

These three challenges derive precisely from what is considered to be the main advantage of the decoherence theory: its open-system perspective, a *bottom-up view* that starts off by considering the open systems and turns to their interaction only later. But the theory can be reformulated from a closed-system perspective [9], a *top-down view* that begins by studying the whole closed system: instead of resorting to reduced states, it focuses on the information of interest by selecting the relevant observables of the closed system. This shows that, despite the successful application of the decoherence formalism to many relevant situations, the question about the meaning of decoherence and the scope of the theory are not matters beyond discussion.

In summary, the debates "decoherence versus interpretation" revolve around whether the theory of decoherence requires interpretive considerations to solve the measurement problem. In general, those discussions take the theory of decoherence for granted, as if it would not involve any difficulty. Therefore, they commonly focus on the "interpretation" wing: even in the case that the open system decoheres in a given basis, the whole closed system is still in a superposition and, thus, without an adequate interpretation, it cannot be said that the observables defined by that basis behave classically. Here we have focused on the "decoherence" wing: given the conceptual challenges that the theory must face and the alternative approaches to the orthodox view, the understanding of the very phenomenon of decoherence still requires a great deal of interpretive work.

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