Foundations of Science (2019) 24:275–285
https://doi.org/10.1007/s10699-018-9574-y

Classicality First: Why Zurek's Existential Interpretation of Quantum Mechanics Implies Copenhagen

Javier Sánchez-Cañizares[1,2]

Abstract
Most interpretations of Quantum Mechanics alternative to Copenhagen interpretation try to avoid the dualistic flavor of the latter. One of the basic goals of the former is to avoid the ad hoc introduction of observers and observations as an inevitable presupposition of physics. Non-Copenhagen interpretations usually trust in decoherence as a necessary mechanism to obtain a well-defined, observer-free transition from a unitary quantum description of the universe to classicality. Even though decoherence does not solve the problem of the definite outcomes, it helps to explain why we do not observe superpositions and, according to Zurek's existential interpretation, why a specific preferred basis emerges through system–environment interactions. The aim of this paper is to show why such interpretation ends up begging the question and provides little progress in understanding the quantum-to-classical transition; the ultimate reason being that preferred bases always correlate to human observation. Benefitting from the technical discussion, some remarks will be offered in the last section regarding the role of classical observations as a necessary condition to make workable the formalism of Quantum Mechanics and scientific activity itself.

Keywords Classicality · Zurek's existential interpretation · Copenhagen interpretation · Preferred basis · Predictive sieve · Quantum-to-classical transition

1 Introduction

After more than a century of quantum physics, the measurement problem or measurement paradox (MP) (Penrose 2004, p. 783)—one of the most notorious conundrums in the foundations of science—remains unsolved. As is well-known, MP reflects an unsatisfactory duality of procedures in Quantum Mechanics (QM), which can be stated as follows within the standard interpretation: there are two basically irreducible processes in the physical description of nature; the deterministic and unitary evolution of the wave-function of a system according to the Schrödinger equation, once the boundary conditions have been

---

✉ Javier Sánchez-Cañizares
js.canizares@unav.es

[1] CRYF Group, Ecclesiastical School of Philosophy, University of Navarra, Pamplona, Spain

[2] Mind-Brain Group, Institute for Culture and Society (ICS), University of Navarra, Pamplona, Spain

established (U-process), and the indeterministic and non-unitary "collapse" of the wave-function after a measurement into one of the possible outcomes regarding that specific measurement (then becoming an actual event) (R-process). The probability of such event is given by the squared amplitude of its correspondent eigenstate in the normalized wave-function before the measurement (Born's rule).

The dualistic flavor of such state of affairs has spurred many different interpretations of QM throughout the last century.[1] It should be stressed from the very beginning that MP directly hints at deep epistemic and ontological questions about whether and how nature determinates itself. The overarching issue is how to reconcile that physical systems cannot, in general, be assigned an exhaustive set of premeasurement values of physical quantities with our intuitively felt need for an 'objectively existing' world around us to which we wish QM to pertain in some way (Schlosshauer 2007, p. 360).

Whereas the standard interpretation remains as a set of instructions which allow for ascertaining the empirical adequacy of the theory without committing to any particular ontological stance, the Copenhagen interpretation (CI)[2] is generally deemed to embrace a strong ontological position regarding classicality of (some parts of) the world—classicality ought to be viewed as an essential and irreducible element of a complete description of the world and, in fact, be considered as a concept prior to QM itself. From Bohr and Heisenberg's times, CI posits the existence of macroscopic apparatuses with well-defined and well-determined possibilities for measuring the relevant system according to the experimenters' will. By contrast, many other subsequent interpretations of QM aim at describing the emergence of classicality from a single unitary quantum perspective, getting rid of process R or at least making it irrelevant and, most interestingly, ruling out the long-lasting dualistic flavor of CI itself.

Launched almost half a century ago by the seminal papers of Zeh (1970) and Zurek (1981, 1982), the "decoherence program" (DP) has never been considered an interpretation of QM. More or less successfully, interpretations do attempt to give an answer to MP in its fullness, embracing different ontological claims. Empirically tested though, decoherence does no give a final response to MP because the reduced density matrix simply offers a pseudo-classical improper mixture of probabilities for a specific measurement. Most physicists agree to acknowledge that DP does not solve the problem of the definite outcomes: why *this* result for *this* specific measure. However, DP's strength tops at its ability to explain why we do not usually observe quantum interference effects in everyday life and, instead, we do observe physical objects with well-defined and determined magnitudes according to probabilities given by Born's rule. Moreover, within Zurek's existential interpretation, it would be ultimately possible to solve the so-called preferred-basis problem for a wave-function initially unbiased towards any choice via the 'predictive sieve' criterion (1998, 2002, 2009). Does Zurek's solution to the problem of the preferred basis make redundant the tenet of CI on the fundamental existence of a classical world, autonomous from and conceptually prior to unitary QM, that need to be combined with the latter?

---

[1] For an affordable description of the most important interpretations see, e.g., the different entries under the heading "Quantum Mechanics" in the *Stanford Encyclopedia of Philosophy*.

[2] When referring to Copenhagen interpretation I will mainly understand Bohr's stance on Copenhagen interpretation regarding classicality, see, e.g. Faye (2014) and Bacciagaluppi (2016). This does not remove generality to the main thesis of this paper because, in this respect, Bohr and Heisenberg agree (Heisenberg 1958, Chapter 3).

My aim in this paper is to show that Zurek's existential interpretation does not succeed by showing in what sense the observation of a classical world remains prior to Zurek's interpretation. Certainly, the relativity of the DP—crucially dependent on the system-environment decomposition—has already been stressed in the literature (Barnum et al. 2003, 2004; Viola and Barnum 2010; Harshman and Ranade 2011; Lombardi et al. 2012; Earman 2015). I will also endorse such view in Sect. 2. However, the essential point of my critiques focuses on the unavoidability of relying in our observations of a classical world for Zurek's solution to work; the reason being that he endorses the predictive sieve criterion by means of the evolutionary perspective.[3] The structure of the paper is as follows: I will explain the framework of the preferred-basis problem making explicit its epistemic and ontological assumptions (Sect. 2). I will then show the epistemic non-pertinence of Zurek's predictive sieve in trying to solve the problem (Sect. 3). Finally, some concluding remarks about what may be learned about the role of observations in QM from the critique of Zurek's interpretation will close the paper (Sect. 4).

2 The Preferred-Basis Problem: Epistemic and Ontological Assumptions

For simplicity, I will focus on an ideal measurement of discrete observables. In that case, the general framework for describing the transition from the quantum to the classical world is the von Neumann scheme for the interaction between a system and a measuring apparatus (either including or not the rest of the world[4]):

$$\sum_i c_i|s_i\rangle \otimes \left|a_{ready}\right\rangle \xrightarrow{\underline{measurement}} \sum_i c_i|s_i\rangle \otimes |a_i\rangle, \tag{1}$$

where $|s_i\rangle$ is an eigenvector of some basis belonging to the Hilbert space of the system and $|a_i\rangle$ is a pointer state of the apparatus. Before the measuring interaction, the system finds itself in the pure state $\sum_i c_i|s_i\rangle$, and $\left|a_{ready}\right\rangle$ represents the state of the apparatus ready to read off the system. Once the measurement interaction between the system and the apparatus has developed, system and apparatus become entangled as expressed by the right hand side of Eq. (1). Orthogonality between the $|a_i\rangle$ states guarantees, among other things, the impossibility of measuring interference between the various $|s_i\rangle$ states of the system.

The inner structure of the tensor product between the two parts as a whole—system and apparatus containing explicit or implicitly the environment—defines whether we can gain some information about one of them. The necessary point in order to have decoherence is the one-to-one correspondence between the local states of the system and the local states of the apparatus (pointer states), as well as the distinguishability (given by the degree of orthogonality) of the latter. Such conditions are fulfilled if the interaction between the system and the apparatus is adequate—this is the fidelity of the measuring apparatus. If that is

---

[3] In that precise sense, my analysis may also help to enlarge the top-down view of the classical limit of QM presented in a recent book (Fortin and Lombardi 2017).

[4] There is no need for the "environment" to be in some sense external to the system. Overall, the macroscopic degrees of freedom of a system can be decohered by the residual degrees of freedom of that same system (Wallace 2008). But this makes the problem of the preferred basis even more pressing: the "residual" degrees of freedom have to be determined in each situation in a practical, non-fundamental, manner.

the case, knowing the (decohered) state of the apparatus allows for knowing the state of the system. But it is important to notice that the existence of a specific "preferred observable" or of a specific "preferred basis" is not fully explained only by the final system–apparatus state arrived at through a von Neumann measurement (Schlosshauer 2007, p. 55).

However, in paying attention to the structure of the quantum formalism it is easy to show that, for a specific apparatus and pointer states $\{|a_i\rangle\}$, some states of the system will be properly entangled and will be able to be measured while others, usually the conjugate states, will not be. We can say that is always true that, for any system-environment decomposition, there will always be some states of the system more prone to decoherence than others and some basis of the system whose eigenvectors are more robust and permanent in the course of the interaction with the environment. "The preferred states of the system emerge dynamically as those states that are the least sensitive, or the most robust, to the interaction with the environment, in the sense that they become least entangled with the environment in the course of the evolution and are thus most immune to decoherence" (Schlosshauer 2007, p. 73; Bacciagaluppi 2016).

But, and this is a big "but", "any density matrix has a host of ontological interpretations. We can never learn, merely from such an argument, that any one of these interpretations provides us with the 'real' state of affairs" (Penrose 2004, p. 803). If one wishes to know which specifically these states are, one has to specifically know how the form of the interaction Hamiltonian is; the general rule being that the preferred basis corresponds to eigenvectors of observables (of the system and the environment) that are locally coupled in the interaction Hamiltonian. In the vast majority of situations, interactions possess a functional dependence on distance (Wallace 2008) and are local in the position observable, favoring the spatial localization of systems of interest.

Apparently, environment-induced decoherence induces effective superselection rules that dynamically emerge from the structure of the system–environment interaction. But it is a matter of detailed physical investigation to assess which systems exhibit which features (Bacciagaluppi 2016). Nevertheless, the intriguing question is why are the interaction Hamiltonians usually functions of local positions in our classical perceived world? This property of locality seems to have crucially appeared in the universe, allowing for the familiar decompositions of system and environment used by science. Note that DP itself derives from the presupposition of the possibility of a meaningful division of the world into 'the system' and 'the environment' (Schlosshauer 2007, p. 101), a division that is always relative (Lombardi et al. 2012). However, if we start from a general wave-function in a general Hilbert space together with a general Hamiltonian evolution and seek for such scientific-friendly decompositions, the answer is appalling: "A state selected at random from the Hilbert space of a many-body system is overwhelmingly likely to exhibit highly non-classical correlations. For these typical states, half of the environment must be measured by an observer to determine the state of a given subsystem. The objectivity of classical reality—the fact that multiple observers can agree on the state of a subsystem after measuring just a small fraction of its environment—implies that the correlations found in nature between macroscopic systems and their environments are exceptional." (Riedel et al. 2012; Tegmark 2015, p. 267) In brief: the initial conditions of the system and/or the form of the Hamiltonian evolution need to be "exceptional." (Tegmark 2015, pp. 265–266).

How does one come to know in practice the Hamiltonian interaction for the system-environment decomposition? The usual answer relies on the correspondence principle: the form of the interaction is surmised from classical physics since QM maintains the algebraic form of the classical interaction potentials albeit in the shape of operators in a Hilbert space. The correspondence principle applies when magnitudes of quantum and classical mechanics are tied up in the limit for very large systems. It helps to ultimately determine the axiomatic formulation of unitary QM by explicitly asking for equivalence between classicality and the quantum description of nature in such macroscopic limit. QM can be developed as a generalization of classical mechanics only if the proviso of the correspondence principle is satisfied. Hence, the correspondence principle should not be understood just as a heuristic tool for theory construction but rather as an epistemological tool, whose "main purpose within Bohr's empirical approach was to bridge the epistemological gap between empirical phenomena and the unknown atomic structure." (Tanona 2004, p. 683).[5]

In a sense, this is hardly surprising: "It would be rather difficult to imagine how an axiomatically introduced 'exact' rule could be able to select preferred bases in a manner that is similarly physically motivated and capable of ensuring empirical adequacy (Schlosshauer 2007, p. 338). The decoherence basis is not effectively specifiable in any precise microphysical way (Wallace 2008). In other words, DP shows the general existence of a preferred basis for each given problem, but cannot pinpoint the specific basis without further interpretation.

3 An Observer-Free Choice of the Preferred Basis?

According to Schlosshauer, "the clear merit of the approach of environment-induced superselection to the preferred-basis problem lies in the fact that the preferred basis is not chosen in an ad hoc manner so as to simply make our measurement records determinate or to match our experience of which physical quantities are usually perceived as determinate (for example, position). Instead the selection is motivated on physical, observer-free grounds, namely, through the structure of the system–environment interaction Hamiltonian." (2007, p. 85.) Classicality would be defined by the agreement of multiple observers on information that is both redundantly and robustly stored in a large number of distinct fragments of the environment, in the spirit of Quantum Darwinism (Zurek 2009). But is this really the case? As said in the previous section, there exists no general criterion for how the total Hilbert space is to be divided into subsystems; the decomposition of system and environment is definitely non-trivial and very likely observer-dependent (Fields 2013). True, the observer cannot arbitrarily choose the observables and must design a measuring device appropriately interacting with the system and the environment, but it does not mean that the preferred basis and measurements are observer-free.

Remarkably, "in trying to explain our observations based on what is predicted by the theory, we may need to give an account of the role of the system that delivers these perceptions to us, namely, the brain." (Schlosshauer 2007, p. 359) We always encounter the core question of why we perceive systems, especially macroscopic ones, in only a tiny subset of the physical quantities in principle allowed by the superposition principle. The question is then not only what makes the instruments suitable for a particular observable but what makes human beings apposite for specific observables. Now, because of the movability of the von Neumann cut, his scheme can be extended to take into account as many interactive parts as one desires. In particular, one may add the observer defined by the concrete physical states forming the neural correlates of his or her observation:

---

[5] For historical and contemporary discussion on Bohr's understanding of the correspondence principle and its different interpretations, see Bokulich (2014).

$$\sum_i c_i |s_i\rangle \otimes \left|a_{ready}\right\rangle \otimes \left|o_{ready}\right\rangle \xrightarrow{observation} \sum_i c_i |s_i\rangle \otimes |a_i\rangle \otimes |o_i\rangle, \tag{2}$$

where $\left|o_{ready}\right\rangle$ stands for $\left|\text{observer}_{ready}\right\rangle$ and $|o_i\rangle$ stands for $|\text{observer perceives measure } s_i\rangle$, s_i being the eigenvalue associated to the eigenstate $|s_i\rangle$.

DP depends on this basic fact: that the most robust states of the systems are properly entangled and correlated with the measuring apparatuses, the environment, and the neural correlates of our observations of measures. Why is it? The answer of Zurek, also assumed by Schlosshauer, is simple: perceiving robust, decoherent-free, quasi-classical states and their quasi-classical trajectories over time means *predictability*,[6] a clear evolutionary advantage. Classicality would have emerged from a long selection process favoring the classical bases according to a principle of optimal information (Durt 2010). Actually, the predictability-sieve strategy—the selection of a set of states characterized by maximal stability or minimal loss of predictive power (Zurek, Habib, and Paz 1993)—provides a general method for determining the preferred states. Let us listen to Zurek's argument nearly identifying classicality and predictability:

> One might still ask why the preferred basis of neurons becomes correlated with the classical observables in the familiar universe. It would be, after all, so much easier to believe in quantum physics if we could train our senses to perceive non-classical superpositions. One obvious reason is that the selection of the available interaction Hamiltonians is limited and constrains the choice of detectable observables. There is, however, another reason for this focus on the classical that must have played a decisive role: Our senses did not evolve for the purpose of verifying quantum mechanics. Rather, they have developed in the process in which survival of the fittest played a central role. There is no evolutionary reason for perception when nothing can be gained from prediction. And, as the predictability sieve illustrates, only quantum states that are robust in spite of decoherence, and hence, effectively classical, have predictable consequences. Indeed, classical reality can be regarded as nearly synonymous with predictability. (Zurek 2002, p. 105).

What is wrong with this argument? The answer is simple: predictability has to do with the content of observations, which has an epistemic value. However, the states represented in Eq. (2)—$|s_i\rangle$, $|a_i\rangle$, $|o_i\rangle$—merely have an ontological value. In the spirit of unitary QM, they simply represent the physical reality; never the *observed* reality. Zurek and Schlosshauer's argument cannot benefit from surreptitiously substituting an ontological state for an epistemic state. The real problem is that the extension of Eq. (1) into Eq. (2) must stop at the level of the physical state corresponding to the neural correlates of the observation—something very different from the content of the observation. There is no place in the quantum formalism for the latter. Consequently, state $\left|\text{observer}_{ready}\right\rangle$ should be labeled $\left|\text{observer's neural correlates}_{ready}\right\rangle$, and state $|\text{observer perceives measure } s_i\rangle$ should be labeled $\left|\text{observer perceives measure } s_i^\prime\text{s neural correlates}\right\rangle$. In other words, the problem that Zurek's interpretation does not and cannot properly tackle appears in the final link between the neural correlates and the content of observations. This link is what allows us

---

[6] As far as I know, Dennett (1991) was the first to establish the functionalist link between "classically perceived reality" and predictability.

to identify the preferred basis—which there must be according to DP—with the usually preferred basis of spatially-localized properties. The problem is that the predictive sieve cannot account, a posteriori, for our subjectively observed preferred basis without assuming, a priori, our subjectively observed preferred basis.

If observations and cognitive prescriptions related to our observational content are not fundamental in unitary QM, what are they? Why do we not observe state vectors of a basis allowing for superpositions of objects in different positions? Zurek's existential interpretation accounts for the inability of the observers to perceive arbitrary superpositions (Zurek 1998, p. 1816) under the assumption that *observers are classical systems observing localized objects*, consequently begging the question. Nevertheless, superpositions of localized vector states could be the most resistant to decoherence if the appropriate factorization of the Hilbert space is considered.[7] This is the quantum factorization problem, which strongly correlates with the existence of conscious observers of a classical reality (Tegmark 2015). Moreover, without the guidance of our observational content, there would be no correspondence principle and no way to (be entitled to) identify the preferred basis with, e.g., a spatially localized basis. Even Zurek acknowledges that "motivation for the predictability sieve comes from the observation that classical states exist or evolve predictably"; the classical domain of the universe might thus be a necessary prerequisite (Zurek 2002).

As it has been recently claimed, MP—encompassing both the definite outcome and the preferred basis problems—and the mind-brain problem might have a subtler connection than commonly believed (Hameroff and Penrose 2014; Sánchez-Cañizares 2014; Ceroni and Prosperi 2018). The hard problem of consciousness (Chalmers 1995) and the interpretive gap might be the hardest because fundamentally linked to the reality and understanding of the quantum-to-classical transition (Tegmark 2015, pp. 264–265). Indeed, if it is a fundamental law that observations are associated with some given basis, the hope of a functional explanation of how observations emerge from basic physics wanes (Wallace 2008). If we were in a position of identifying the content of an observation with an ontic, physical state could we expect to fully describe the emergence of classicality from an underlying quantum reality homogeneously described by the unitary U-process. But a physical explanation about why the one-to-one link between some firing pattern of neurons, the physical state of the brain, and the localized physical states of the observed system give rise to an observational content of localized physical states of the system is lacking: "QM itself does not allow us to derive a relationship between subjective experience and its physical correlates." (Schlosshauer 2007, p. 376).

Still, one could argue, predictability is simply a subjective proxy for objective stability. The criterion to single out the preferred basis could be objectively stated when one takes into account that the preferred basis is constituted by states that minimize the entropy production (Schlosshauer 2007, p. 82). The weakness of such argument is the alleged objective status of the definition of entropy. Quite the contrary, there is no universal definition of entropy previous to the system-environment decomposition, in which classicality already seems at play (Tanona 2013). There is a priori no universal definition of entropy to be optimized in all problems. Such principle depends on the different constraints of the system and its degrees of freedom. Recourse to entropy minimization is just a pragmatic approach

---

[7] Given an abstract Hilbert space and Hamiltonian, we could envisage a system-environment partition where the preferred basis is de-localized, i.e. formed by superpositions of localized vector states. In Schrödinger-cat terms, had we not observations, we would be a priori equally entitled to use as basis the superpositions of dead cat and live cat.

lacking sounder foundations (Dewar et al. 2014). In that regard, Zurek must at least be credited by underscoring the necessary link between stability and predictability, equating them for practical purposes.

4 Concluding Remarks

What can be learned about the role of observations in QM from the criticism of Zurek's interpretation? More than a decade ago, Landman claimed that decoherence cannot stand on their own in explaining the appearance of the classical world: "a full explanation of the classical world from quantum theory is still in its infancy." (Landsman 2007, pp. 529–530) Perhaps adulthood will never come because it is not simply a matter of accepting the pacific coexistence of the quantum and the classical realms for the time being (Paty 2000). DP does not provide an ontology for QM. Relying on decoherence can be useful to make sense of interpretations of QM only inasmuch as the classicality criterion—the guiding role of the perception of classicality—is fully respected. But the content of observations cannot be accounted for by DP alone.

From the viewpoint of philosophy of science, one may recall the insufficiencies of the "appearance from reality" criterion.[8] The ability to self-attribute a position with respect to the representation is the condition of possibility of use of that representation. To use a theory or model, to base predictions on it, we have to locate ourselves with respect to it. If a scientific theory aims to represent nature, scientists need to self-attribute their position in that very representation. Scientific models can thus hardly expect to achieve isomorphism with the whole nature (van Fraassen 2008, pp. 257–292). Instead, the "appearance *of* reality" is a key ingredient not just for empirical adequacy as the ultimate truth maker, but as guiding principle for selection and definition of relevant and workable problems.

By cross-examining Zurek's existential interpretation, I have tried in this paper to track back into the realm of first physical principles what an observation is. The technical problem with Zurek's account of classicality can be summarized as follows: our senses, our neural correlates of what is perceived (epistemic) need to be entangled (as pointer states) with what is perceived (ontological). We can only perceive if our neural correlates are one-to-one entangled with (some perceived properties of) the underlying reality. Such entanglement is a *necessary* condition for observation but it is not *sufficient*, i.e. it is obviously not necessarily true that if my neural correlates are one-to-one entangled with (some properties of) the underlying reality I will necessarily perceive those (decohered) properties. For that last statement to be true, we would need to have a unitary quantum–mechanical account of how the content of any observation emerges from a unique quantum reality.

True, CI does not provide an answer to what an observation is. However, it has the virtue of highlighting that observations are non-reducible parts of the scientific endeavor and classicality is not to be derived as the macroscopic limit of an underlying

---

[8] [T]he Copenhagen development of quantum theory exemplifies a clear rejection of the [Appearance from Reality] Criterion. The famous Measurement Problem in the philosophy of quantum mechanics is not a problem from an empiricist point of view (…).The rejection may not be unique in the history of science, but is brought home to us inescapably by the advent of the new quantum theory. Even if that theory is superseded (or if fundamental physics develops in accordance with a new interpretation under which the Criterion can be satisfied) our view of science must be forever modified in the light of this historical episode. (van Fraassen 2008, p. 292).

unitary quantum process. Observations play an essential and primary role in science, not just in the sense of obtaining information to test our predictions. Either if the very act of observation plays a role in determining nature or if the observation simply reads off what is already determined, it first tells us what ultimately needs to be explained. Whereas classical physics had only to account for the concrete values taken by some quantities—naïvely clinging to a one-to-one correspondence between reality and theory—, QM needs to explain the emergence of such concrete classical quantities. That would be unnecessary were it not for our observation of localized objects in space–time.

Zurek's existential interpretation of QM explains why we do not perceive interference or superposition effects *under the assumption that our senses are evolutionarily tuned to perceive a classical world*. But then, Zurek's argument based on the evolutionary advantages of predictability hits a serious setback. Not only has it more a pragmatic than a fundamental character (Wallace 2012); the crux of the issue is that an epistemic argument, namely predictability, may not be used in a purely physical discussion about the emergence of a specific preferred basis from unitary QM. Even though physics underlies all observation, the observational content does not equate to its physical substrate. To dispense with classicality one should first physically explain what an observation is—as something whose content is different from its neural correlates—and how observations emerged and evolved in the universe. If that proves impossible, the emerging picture of decoherence fits substantially better Bohr and Heisenberg's Copenhagen interpretation than other interpretations—contrary to Zurek's opinion (1998, p. 1817). Decoherence implies Bohr and Heisenberg's intuition that QM requires a classical domain. In such request, the founding fathers saw further than all kinds of non-Copenhagen interpreters:

> [I]t has sometimes been suggested that one should depart from the classical concepts altogether and that a radical change in the concepts used for describing the experiments might possibly lead back to a nonstatical [sic], completely objective description of nature. This suggestion, however, rests upon a misunderstanding. The concepts of classical physics are just a refinement of the concepts of daily life and are an essential part of the language which forms the basis of all natural science. Our actual situation in science is such that we do use the classical concepts for the description of the experiments, and it was the problem of quantum theory to find theoretical interpretation of the experiments on this basis. There is no use in discussing what could be done if we were other beings than we are. (…) Our scientific work in physics consists in asking questions about nature in the language that we possess and trying to get an answer from experiment by the means that are at our disposal. (Heisenberg 1958, pp. 55–57).

References

Bacciagaluppi, G. (2016). The role of decoherence in quantum mechanics. In E. N. Zalta (Ed.), *The stanford encyclopedia of philosophy*. https://plato.stanford.edu/archives/fall2016/entries/qm-decoherence/. Accessed 5 Sept 2018.

Barnum, H., Knill, E., Ortiz, G., Somma, R., & Viola, L. (2004). A subsystem-independent generalization of entanglement. *Physical Review Letters, 92,* 107902.

Barnum, H., Knill, E., Ortiz, G., & Viola, L. (2003). Generalizations of entanglement based on coherent states and convex sets. *Physical Review A, 68,* 032308.

Bokulich, A. (2014). Bohr's correspondence principle. In E. N. Zalta (Ed.), *The stanford encyclopedia of philosophy*. https://plato.stanford.edu/archives/spr2014/entries/bohr-correspondence/. Accessed 5 Sept 2018.

Ceroni, M., & Prosperi, G. M. (2018). Free will, subjectivity and the physics of the nervous system. *Open Journal of Philosophy, 8,* 317–341.

Chalmers, D. J. (1995). Facing up to the problem of consciousness. *Journal of Consciousness Studies, 2*(3), 200–219.

Dennett, D. C. (1991). Real patterns. *Journal of Philosophy, 87,* 27–51.

Dewar, R. C., Lineweaver, C. H., Niven, R. K., & Regenauer-Lieb, K. (2014). Beyond the second law: An overview. In R. C. Dewar, C. H. Lineweaver, R. K. Niven, & K. Regenauer-Lieb (Eds.), *Beyond the second law. Entropy production and non-equilibrium systems* (pp. 15–27). Berlin: Springer.

Durt, T. (2010). Anthropomorphic quantum Darwinism as an explanation for classicality. *Foundations of Science, 15*(2), 177–197.

Earman, J. (2015). Some puzzles and unresolved issues about quantum entanglement. *Erkenntnis, 80,* 303–337.

Faye, J. (2014). Copenhagen interpretation of quantum mechanics. In E. N. Zalta (Ed.), *The stanford encyclopedia of philosophy*. https://plato.stanford.edu/archives/fall2014/entries/qm-copenhagen/. Accessed 5 Sept 2018.

Fields, C. (2013). On the Ollivier–Poulin–Zurek Definition of objectivity. *Axiomathes, 24,* 137–156.

Fortin, S., & Lombardi, O. (2017). A top-down view of the classical limit of quantum mechanics. In R. E. Kastner, J. Jeknić-Dugić, & G. Jaroszkiewicz (Eds.), *Quantum structural studies* (pp. 435–468). Europe: World Scientific.

Hameroff, S., & Penrose, R. (2014). Consciousness in the universe: A review of the 'Orch OR' theory. *Physics of Life Reviews, 11*(1), 39–78.

Harshman, N., & Ranade, K. (2011). Observables can be tailored to change the entanglement of any pure state. *Physical Review A, 84,* 012303.

Heisenberg, W. (1958). *Physics and philosophy. The revolution in modern science*. London: Unwin University Books.

Landsman, N. P. (2007). Between classical and quantum. In J. Butterfield & J. Earman (Eds.), *Handbook of the philosophy of science: Philosophy of physics* (pp. 417–553). Amsterdam: Elsevier.

Lombardi, O., Fortín, S., & Castagnino, M. (2012). The problem of identifying the system and the environment in the phenomenon of decoherence. In H. W. de Regt, S. Hartmann, & S. Okasha (Eds.), *The european philosophy of science association proceedings: Amsterdam 2009* (pp. 161–174). Berlin: Springer.

Paty, M. (2000). The quantum and classical domains as provisional parallel coexistents. *Synthese, 125,* 179–200.

Penrose, R. (2004). *The road to reality. A complete guide to the laws of the universe*. London: Jonathan Cape.

Riedel, C. J., Zurek, W. H., & Zwolak, M. (2012). The rise and fall of redundancy in decoherence and quantum Darwinism. *New Journal of Physics, 14,* 083010.

Sánchez-Cañizares, J. (2014). The mind-brain problem and the measurement paradox of quantum mechanics: Should we disentangle them? *NeuroQuantology, 12*(1), 76–95.

Schlosshauer, M. (2007). *Decoherence and the quantum-to-classical transition*. Heidelberg: Springer.

Tanona, S. (2004). Idealization and formalism in Bohr's approach to quantum theory. *Philosophy of Science, 71*(December), 683–695.

Tanona, S. (2013). Decoherence and the Copenhagen cut. *Synthese, 190,* 3625–3649.

Tegmark, M. (2015). Consciousness as a state of matter. *Chaos, Solitons & Fractals, 76,* 238–270.

van Fraassen, B. C. (2008). *Scientific representation: Paradoxes of perspective*. Oxford: Clarendon Press.

Viola, L., & Barnum, H. (2010). Entanglement and subsystems, entanglement beyond subsystems, and all that. In A. Bokulich & G. Jaeger (Eds.), *Philosophy of quantum information and entanglement* (pp. 16–43). Cambridge: Cambridge University Press.

Wallace, D. (2008). Philosophy of quantum mechanics. In D. Rickles (Ed.), *The ashgate companion to the new philosophy of physics* (pp. 16–98). Aldershot: Ashgate.

Wallace, D. (2012). Decoherence and its role in the modern measurement problem. *Philosophical Transactions of the Royal Society of London A, 370,* 4576–4593.

Zeh, H. D. (1970). On the interpretation of measurement in quantum theory. *Foundations of Physics, 1,* 69–76.

Zurek, W. H. (1981). Pointer basis of quantum apparatus: Into what mixture does the wave packet collapse? *Physical Review D, 24,* 1516–1525.

Zurek, W. H. (1982). Environment-induced superselection rules. *Physical Review D, 26,* 1862–1880.

Zurek, W. H. (1998). Decoherence, einselection, and the existential interpretation (the rough guide). *Philosophical Transactions of the Royal Society of London A, 356,* 1793–1821.

Zurek, W. H. (2002). Decoherence and the transition from quantum to classical—revisited. *Los Alamos Science, 27,* 86–109.

Zurek, W. H. (2009). Quantum Darwinism. *Nature Physics, 5,* 181–188.

Zurek, W. H., Habib, S., & Paz, J. P. (1993). Coherent states via decoherence. *Physical Review Letters, 70,* 1187–1190.

Javier Sánchez-Cañizares has obtained a Ph.D. in Physics (Universidad Autónoma de Madrid, 1999) and a Ph.D. in Theology (Pontifical University of the Holy Cross, Rome 2006). He is currently professor of "Science, Reason and Faith" (CRYF) and researcher of the "Mind-Brain" Group of the Institute for Culture and Society (ICS) at the University of Navarra. He has published more than 60 research articles and books in physics, philosophy and theology. His main interests are in the relations between science and religion, the philosophy of nature and the relevance of Quantum Mechanics for the understanding of human singularity in the universe. In 2018, he has received the Expanded Reason Award in the category of research for his work "Singular Universe". For more information, see http://www.unav.es/cv/js.canizares.