Quantum Superpositions and Causality:
On the Multiple Paths to the Measurement Result

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Abstract

The following analysis attempts to provide a general account of the multiple solutions given to the quantum measurement problem in terms of causality. Leaving aside instrumentalism which restricts its understanding of quantum mechanics to the algorithmic prediction of measurement outcomes, the many approaches which try to give an answer can be distinguished by their explanation based on the *efficient cause* —recovering in this way a classical physical description— or based on the *final cause* —which goes back to the hylomorphic tradition. Going beyond the limits of these two schemes we call the attention to an 'inversion of the measurement problem' and its proposed solution based on the *immanent cause*. By replacing both the final and efficient causes by the immanent cause we attempt to lay down new conditions for representing quantum superpositions in a realist way which coherently relates the quantum formalism with outcomes.

Keywords: quantum superposition, causality, measurement problem.

Introduction

Quantum states are the key mathematical objects in quantum mechanics (QM). Strange as it might seem, more than one century after its creation, nor physicists nor philosophers of physics agree on what a quantum state represents [37]. In the orthodox formulation of QM, the representation of the state of a system is given by a ray in Hilbert space $\mathcal{H}$. Contrary to

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the classical scheme, physical magnitudes are represented by operators on $\mathcal{H}$ that, in general, do not commute. This mathematical fact has extremely problematic interpretational consequences for it is then difficult to affirm that these quantum magnitudes are *simultaneously preexistent*. In order to restrict the discourse to different sets of commuting magnitudes, different Complete Sets of Commuting Operators (CSCO) have to be chosen. The choice of a particular representation (given by a CSCO) determines the basis in which the observables diagonalize and in which the ray can be expressed. Thus, the ray can be written as different linear combinations of states:

$$\alpha_i|\varphi_i^{B1}> + \alpha_j|\varphi_j^{B1}> = |\varphi_q^{B2}> = \beta_m|\varphi_m^{B3}> + \beta_n|\varphi_n^{B3}> + \beta_o|\varphi_o^{B3}> \quad (1)$$

The linear combinations of states are also called quantum superpositions. In an earlier paper we have concentrated our analysis focusing on the meaning of quantum superpositions and the different interpretations found in the literature [10]. Unfortunately, instead of reflecting about the possible understanding of superpositions, many approaches have concentrated their efforts in justifying the fact that, quite independently of the physical interpretation of quantum superpositions, at the end of a measurement there is always a single pointer position marking a definite result. This is one of the most important debates in the literature, the so called "measurement problem". In the following, we attempt to provide a general account on the multiple solutions given to the measurement problem as related to its causal explanation. As we shall see, the many approaches can be distinguished by their explanation based on the *efficient cause* —recovering in this way a classical physical description of QM— or on the *final cause* —a solution going back to the hylomorphic tradition which recovers the potential realm. Going beyond the limits of hylomorphism, actualism and the instrumentalist account provided in terms of measurement outcomes, we attempt to invert the measurement problem providing a solution to this new problem in terms of the *immanent cause*. By replacing both the final and efficient causes by the immanent cause we attempt to lay down new conditions for representing quantum superpositions in a way which coherently relates the quantum formalism with outcomes.

In section 1, we provide a general account of hylomorphism which relates, through the final cause the potential and actual realms. In section 2, we discuss how, in Newtonian mechanics, the realm of potentiality was completely eliminated, actuality becoming —through the efficient cause—

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the only relevant mode of existence for physical description. In section 3 we discuss the historical background surrounding the collapse of the quantum wave function and the projection postulate. Section 4 analyzes the meaning of the projection postulate and its physical interpretation in terms of 'collapse solutions' and 'non-collapse solutions' making special emphasis on the causal explanation which each of these proposals brings into stage. Section 5 presents an original solution to the relation between quantum superpositions and measurement outcomes through the introduction of the *immanent cause*, *powers* and *potential effectuations*. Finally, in section 6, we present the conclusions of the paper.

1   Hylomorfism and the Final Cause: From Potentiality to Actuality

The debate in Pre-Soctratic philosophy is traditionally understood as the contraposition of the Heraclitean and the Eleatic schools of thought. Heraclitus was considered as defending the theory of flux, a doctrine of permanent motion, change and unstability in the world. This doctrine precluded, as both Plato and Aristotle stressed repeatedly, the impossibility to develop certain knowledge about the world. In contraposition to the Heraclitean school we find Parmenides as the main character of the Eleatic school. Parmenides, as interpreted also by Plato and Aristotle, taught the non-existence of motion and change in reality, reality being absolutely One, and being absolutely Being. In his famous poem Parmenides stated maybe the earliest intuitive exposition of the **principle of non-contradiction**; i.e. that which *is* can only *be*, that which *is not, cannot be.* In order to dissolve the problem of movement, Aristotle developed a metaphysical scheme in which, through the notions of *actuality* and *potentiality*, he was able to articulate both the Heraclitean and the Eleatic schools. On the one hand, potentiality contained the undetermined, contradictory and non-individual realm of existence, on the other, the mode of being of actuality was determined through the logical **principles of existence**, **non-contradiction** and **identity**, it was through these principles that the concept of entity was put forward. The notion of entity is capable of unifying, of totalizing in terms of a "sameness", creating certain stability for knowledge to be possible. This representation or transcendent description of the world is considered by many the origin of metaphysical thought. Actuality is then linked directly to metaphysical representation and understood as characterizing a mode of existence inde-

pendent of observation. This is the way through which metaphysical thought was able to go beyond the *hic et nunc*, creating a world beyond the world, a world of concepts.

In the book Θ of *Metaphysics*, Aristotle [1046b5-1046b24] remarks there are two types of potentiality: "[...] some potentialities will be non-rational and some will be accompanied by reason." For obvious reasons Aristotle calls these two potentialities 'rational' and 'irrational'. Irrational potentiality implies a realm of 'indefiniteness', a realm of 'incompleteness' and 'lack'. It is only when turning into actuality, that the potential is fulfilled, completed (e.g. the child becoming a man, the seed transforming into a tree) [1047b3-1047b14]. The path from irrational potentiality into actualization may be related to the *process* through which *matter* turns into *form*. The matter of a substance being the stuff it is composed of; the form, the way that stuff is put together so that the whole it constitutes can perform its characteristic functions. Through this passage substance becomes more perfect and, in this way, closer to God, *pure acto* [1051a4-1051a17].[1] Because of this it makes no sense to consider the realm of irrational potentiality independently of actuality. Final causality is the link which allows to close the gap in between both realms. Almost forgotten in the literature, which discusses the notion of potentiality almost exclusively in terms of irrational potentiality, the notion of rational potentiality is characterized by Aristotle as related to the problem of possessing a capability, a faculty [1046b5-1046b24], to what I mean when I say: "I can", "I cannot". As explicitly noticed by Aristotle, potentiality implies a mode of existence which must be considered as real as actuality. In chapter 3 of book Θ of *Metaphysics* Aristotle introduces the notion of rational potentiality as independent to the actual realm.[2] That

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[1]As noticed by Verelst and Coecke [50, p. 168]: "change and motion are intrinsically not provided for in this [Aristotelian logical] framework; therefore the ontology underlying the logical system of knowledge is essentially static, and requires the introduction of a First Mover with a proper ontological status beyond the phenomena for whose change and motion he must account for." This first mover is God, *pure acto*, pure definiteness and form without the contradiction and evil present in the potential matter.

[2]Aristotle goes against the Megarians who considered actuality as the only mode of existence: "There are some who say, as the Megaric school does, that a thing can act only when it is acting, and when it is not acting it cannot act, e.g. he who is not building cannot build, but only he who is building, when he is building; and so in all other cases. It is not hard to see the absurdities that attend this view. For it is clear that on this view a man will not be a builder unless he is building (for to be a builder is to be able to build), and so with the other arts. If, then, it is impossible to have such arts if one has not at some time learnt and acquired them, and it is then impossible not to have them if one has not sometime lost them (either by forgetfulness or by some accident or by time; for it

which exists within rational potentiality is then characterized as being capable of both contrary effects.[3] This also means that potentiality is capable of being and not being at one and the same time.[4] The contradiction of being and not being present in rational potentiality is only dissolved when, considering the actual realm, one of the terms is effectuated. Contrary to the case of irrational potentiality, where a teleological cause places the end in actuality, rational potentiality might be interpreted as a realm independent of actuality.

However, although Aristotle presented at first both actual and potential realms as ontologically equivalent, from chapter 6 of book Θ, he seems to place actuality in the central axis of his architectonic, relegating potentiality to a mere supplementary role. "We have distinguished the various senses of 'prior', and it is clear that actuality is prior to potentiality. [...] For the action is the end, and the actuality is the action. Therefore even the word 'actuality' is derived from 'action', and points to the fulfillment." [1050a17-1050a23] Aristotle then continues to provide arguments in this line which show "[t]hat the good actuality is better and more valuable than the good potentiality." [1051a4-1051a17] The choice of Aristotle to take irrational

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cannot be by the destruction of the object itself, for that lasts for ever), a man will not have the art when he has ceased to use it, and yet he may immediately build again; how then will he have got the art? [...] evidently potentiality and actuality are different; but these views make potentiality and actuality the same, so that it is no small thing they are seeking to annihilate. [...] Therefore it is possible that a thing may be capable of being and not be, and capable of not being and yet be, and similarly with the other kinds of predicate; it may be capable of walking and yet not walk, or capable of not walking and yet walk." [1046b29 - 1047a10]

[3] "Since that which is capable is capable of something and at some time and in some way —with all the other qualifications which must be present in the definition—, and since some things can work according to a rational formula and their potentialities involve a formula, while other things are non-rational and their potentialities are non-rational, and the former potentialities must be in a living thing, while the latter can be both in the living and in the lifeless; as regards potentialities of the latter kind, when the agent and the patient meet in the way appropriate to the potentiality in question, the one must act and the other be acted on, but with the former kind this is not necessary. For the non-rational potentialities are all productive of one effect each, but the rational produce contrary effects, so that they would produce contrary effects at the same time; but this is impossible. That which decides, then, must be something else; I mean by this, desire or choice." [1048a1-1048a24]

[4] "Every potentiality is at one and the same time a potentiality for the opposite; for, while that which is not capable of being present in a subject cannot be present, everything that is capable of being may possibly not be actual. That, then, which is capable of being may either be or not be; the same thing, then, is capable both of being and of not being." [1050b7-1050b28]

potentiality and the final cause as the basis of his metaphysics determined the fate of western thought.

2 Classical Physics and the Efficient Cause: The End of the Potential Realm

The importance of (irrational) potentiality, which was a central element in Aristotle's scheme was soon diminished in the history of western thought. As we have seen above, it could be argued that the seed of this move was already present in the Aristotelian architectonic, whose focus was clearly placed in the actual realm. In relation to the development of physics, the focus and preeminence was also given to actuality. The XVII century division between 'res cogitans' and 'res extensa' played in this respect an important role separating very clearly the realms of actuality and potentiality. The realm of potentiality, as a different (ontological) mode of the being, was neglected becoming not more than mere (logical) *possibility*. The philosophy which was developed after Descartes kept 'res cogitans' (thought) and 'res extensa' (entities as acquired by the senses) as separated realms.[5]

> "Descartes knew the undisputable necessity of the connection, but philosophy and natural science in the following period developed on the basis of the polarity between the 'res cogitans' and the 'res extensa', and natural science concentrated its interest on the 'res extensa'. The influence of the Cartesian division on human thought in the following centuries can hardly be overestimated, but it is just this division which we have to criticize later from the development of physics in our time."
> [24, p. 73]

This materialistic conception of science based itself on the main idea that extended things exist as being definite, that is, in the actual realm of existence. With modern science the actualist Megarian path was recovered and potentiality dismissed as a problematic and unwanted guest. The transformation from medieval to modern science coincides with the abolition of Aristotelian hylomorphic metaphysical scheme —in terms of potentiality and actuality— as the foundation of knowledge. However, the basic structure of Aristotelian logic still remained the basis for correct reasoning. As noted by Verelst and Coecke:

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[5]While 'res cogitans', the soul, was related to the *indefinite* realm of potentiality, 'res extensa', i.e. the entities as characterized by the principles of logic, related to the actual.

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"Dropping Aristotelian metaphysics, while at the same time continuing to use Aristotelian logic as an empty 'reasoning apparatus' implies therefore loosing the possibility to account for change and motion in whatever description of the world that is based on it. The fact that Aristotelian logic transformed during the twentieth century into different formal, axiomatic logical systems used in today's philosophy and science doesn't really matter, because the fundamental principle, and therefore the fundamental ontology, remained the same. This 'emptied' logic actually contains an Eleatic ontology, that allows only for static descriptions of the world." [50, p. 7]

It was Isaac Newton who was able to translate into a closed mathematical formalism both, the ontological presuppositions present in Aristotelian (Eleatic) logic and the materialistic ideal of 'res extensa' together with actuality as its mode of existence. In classical mechanics the representation of the state of the physical system is given by a point in phase space Γ and the physical magnitudes are represented by real functions over Γ. These functions commute in between each others and can be interpreted as possessing definite values independently of measurement, i.e. each function can be interpreted as being actual. The term actual refers here to *preexistence* (within the transcendent representation) and not to the observation *hic et nunc*. Every physical system may be described exclusively by means of its actual properties. The change of the system may be described by the change of its actual properties. Thus, potential or possible properties are considered only as the points to which the system might arrive in a future instant of time. As also noted by Dieks:

"In classical physics the most fundamental description of a physical system (a point in phase space) reflects only the actual, and nothing that is merely possible. It is true that sometimes states involving probabilities occur in classical physics: think of the probability distributions ρ in statistical mechanics. But the occurrence of possibilities in such cases merely reflects our ignorance about what is actual. The statistical states do not correspond to features of the actual system (unlike the case of the quantum mechanical superpositions), but quantify our lack of knowledge of those actual features." [15, p. 124]

Classical mechanics tells us via the equation of motion how the state of the system moves along the curve determined by the initial conditions in Γ and

thus, as any mechanical property may be expressed in terms of Γ's variables, how all of them evolve. Moreover, the structure in which actual properties may be organized is the (Boolean) algebra of classical logic. Newtonian mechanics had not only done away with free will but also with the *final cause* which governed the most important part of Aristotle's scheme. Instead, it was now the *efficient cause* which was capable of articulating the evolution of actualities. In each instant of time the world was constituted by definite valued properties, i.e. an *actual state of affairs*.

3 Those "Damned Quantum Jumps!" and the End of Representation

The rise of QM in 1900 placed, since its origin, serious difficulties in order to maintain an account of physical reality in terms of an actual state of affairs. The quantum principle of Planck had shaken the very foundation of Newtonian physics. Discreetness precluded a description in terms of space and time while indeterminacy threatened to break down the classical physical explanation in terms of the *efficient cause*. Nevertheless such non-classical principles were used in order to advance in the theory. Einstein was one of the first to make use of the quantum principle explaining through it the photoelectric effect in 1905, Bohr also used the quantum postulate in his 1913 model of the atom and even Heisenberg developed his matrix mechanics and the indeterminacy principle in 1925 starting from the discrete character of the quantum. The development of quantum theory, based on such non-classical standpoints was clearly threatening the ideal of physics as a representation of the world. Many, including Einstein were certainly uncomfortable with this situation.

A new hope to recover physical representation was born with Schrödinger's wave mechanics, but it was soon clear, especially after Born's interpretation of the quantum wave function in terms of a probability density, that the quantum jumps were here to stay. Schrödinger is then quoted to have said: "Had I known that we were not going to get rid of this damned quantum jumping, I never would have involved myself in this business!" Indeed, he had understood very clearly the fact that the acceptance of causal indetermination seemed to preclude the possibility of a visualizable representation of the theory. In this respect QM introduced a strong debate between those who wanted to continue having, in different ways, physics as a description of the world —such as Einstein, Schrödinger, de Broglie and Pauli— and those

who, for very different reasons —such as Bohr, Born and Dirac[6]— did not mind loosing the ideal of representation, provided the theory did the job of predicting, at least probabilistically, the measurement outcomes of a given experimental arrangement. The first stance had their attempts proposed, firstly, by Louis de Broglie in 1924 with his pilot wave theory, and secondly by Schrödinger, at the beginning of 1927, when he put forward his wave mechanics —both attempts supported by Einstein. But indeed, both proposals had very clear and difficult problems to overcome and match a descriptive coherent interpretation of phenomena. The second stance had stood on the critic put forward by Ernst Mach to the use of dogmatic metaphysical concepts —e.g., Newtonian absolute space and time. Instead, Mach had called for a recovery of a sensualistic science based on observability alone. Certainly, the idea that observable magnitudes had to be considered in the formalism of the theory, was the key Heisenberg had used to arrive to his matrix mechanics —later on developed by Max Born, Pascual Jordan and himself in 1926. Matrix mechanics seemed to be non-visualizable and abstract for the physicists of the time, accustomed to work with differential equations [38]. Born —a mathematician himself— was happy to have found a closed consistent mathematical formalism, that was enough for him. But it was not enough for Einstein whose research was based on a visualizable theory. At the end of 1927 Niels Bohr had come up with an explanation of his own using the notion of complementarity, which focused in fulfilling the consistency requirements of the quantum formalism to apply the well known classical descriptions in terms of waves and particles [5]. According to Bohr [54, p. 7]: "[...] the unambiguous interpretation of any measurement must be essentially framed in terms of classical physical theories, and we may say that in this sense the language of Newton and Maxwell will remain the language of physicists for all time." Bohr had found a new *a priori*: classical language —which would serve to secure intersubjectivity. But, in order to close the circle, no "new language" was allowed from now on to enter the scene: "it would be a misconception to believe that the difficulties of the atomic theory may be evaded by eventually replacing the concepts of classical physics by new conceptual forms." [54, p. 7] Heisenberg's uncertainty relations —understood epistemically by Bohr [25]— would then secure the knowledge provided by the more general principle of complemen-

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[6]Heisenberg might be regarded as a highly pragmatic character who shifted from an epistemological position close to that of Bohr to some kind of Platonic realism about mathematical symmetries and structures.

tarity. Bohr had regained objectivity by watching quantum theory from a distance, standing on the well known heights of classical language. However, the position of Bohr presented a very unclear relation between the classical world and the quantum formalism, which, according to Bohr, did not seem to have a place in the classical conception of the world, but nevertheless, talked about it in terms of measurement outcomes.

Quite independently of the many problems which remained for a coherent interpretation the story was told and repeated once and again, that loosing representation was not so bad after all. As it is clearly stated by Fine, this war was won by Bohr:

> "In the body of the paper [from 1925], Heisenberg not only rejects any reference to un-observables; he also moves away from the very idea that one should try to form any picture of a reality underlying his mechanics. To be sure, Schrödinger, the second father of quantum theory, seems originally to have had a vague picture of an underlying wavelike reality for his own equation. But he was quick to see the difficulties here and, just as quickly, although reluctantly, abandoned the attempt to interpolate any reference to reality. These instrumentalist moves, away from a realist construal of the emerging quantum theory, were given particular force by Bohr's so-called philosophy of complementarity; and this non-realist position was consolidated at the time of the famous Solvay conference, in October of 1927, and is firmly in place today. Such quantum non-realism is part of what every graduate physicist learns and practices. It is the conceptual backdrop to all the brilliant successes in atomic, nuclear, and particle physics over the past fifty years. Physicists have learned to think about their theory in a highly non-realist way, and doing just that has brought about the most marvelous predictive success in the history of science." [22, p. 88]

Today, the so called "Copenhagen Interpretation of QM"[7] is taught in Universities all around the world. Put in a nutshell this "interpretation" tells us

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[7]The idea of a common interpretation of the founding fathers is difficult to maintain. Don Howard's research has brought some light to the creation of what he calls the "Copenhagen Myth" [26]. As remarked by Jones, the interpretation and development of QM "was never a team effort. Sometimes, two or three would collaborate for a while, but mostly they were rivals who wanted their particular version of the new science to prevail. They had little enough in common." [38, p. 10].

how, following a set of postulates,[8] one can calculate all probability outcomes of a given experimental arrangement. The fifth is the so called **projection postulate** (**PP**) which makes explicit —as a reminder of the still unsolved problems— those "damned quantum jumps!"

4   Quantum Superpositions and the Projection Postulate: To Collapse or Not to Collapse?

Classical texts that describe QM axiomatically begin stating that the mathematical interpretation of a quantum system is a Hilbert space, that pure states are represented by rays in this space, physical magnitudes by self-adjoint operators on the state space and that the evolution of the system is ruled by the Schrödinger equation. Possible results of a given magnitude are the eigenvalues of the corresponding operator obtained with probabilities given by the Born rule. In general, the state previous to the measurement is a linear superposition of eigenstates corresponding to different eigenvalues of the measured observable. In order to give an account of the state of the system after the appearance of a particular result one needs to add the **PP**. In von Neunmann's [53, p. 214] words: "Therefore, if the system is initially found in a state in which the values of $\mathcal{R}$ cannot be predicted with certainty, then this state is transformed by a measurement M of $\mathcal{R}$ into another state: namely, into one in which the value of $\mathcal{R}$ is uniquely determined. Moreover, the new state, in which M places the system, depends not only on the arrangement of M, but also on the result of M (which could not be predicted causally in the original state) —because the value of $\mathcal{R}$ in the new state must actually be equal to this M-result".[9] At this point one needs to also introduce the so called **Eigenstate-Eigenvalue Link (EEL):** *after the measurement, the state of the system is that (i.e., the eigenstate) which corresponds to the measured eigenvalue.* There are different ways to provide a physical account of the projection postulate. One of the main distinctions made in the literature is in between the so called "collapse solutions" which consider the **PP** as a real physical interaction which takes place dur-

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[8]See for example the orthodox texts: [9, 43].

[9]Or in Dirac's words: "When we measure a real dynamical variable ξ, the disturbance involved in the act of measurement causes a jump in the state of the dynamical system. From physical continuity, if we make a second measurement of the same dynamical variable ξ immediately after the first, the result of the second measurement must be the same as that of the first." [16, p. 36]

ing measurement, and "non-collapse solutions" which retain superpositions independently of actual observations.

4.1   Collapse Solutions and the Return of the Final Cause

Collapse interpretations have its most important proponent in orthodoxy, a pseudo-instrumentalist perspective which goes —unfortunately— many times by the name of "the Copenhagen interpretation of QM". This scheme accepts without any clear argument the idea of a "collapse" taking place during measurement (i.e., as a real physical stochastic "jump" from the state previous to the measurement to the eigenstate corresponding to the measured eigenvalue). One of the most known interpretations of the collapse was provided by Heisenberg:

> "The observation itself changes the probability function discontinuously; it selects of all possible events the actual one that has taken place. Since through the observation our knowledge of the system has changed discontinuously, its mathematical representation also has undergone the discontinuous change and we speak of a 'quantum jump.' When the old adage 'Natura non facit saltus' is used as a basis for criticism of quantum theory, we can reply that certainly our knowledge can change suddenly and that this fact justifies the use of the term 'quantum jump.'
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> Therefore, the transition from the 'possible' to the 'actual' takes place during the act of observation. If we want to describe what happens in an atomic event, we have to realize that the word 'happens' can apply only to the observation, not to the state of affairs between two observations. It applies to the physical, not the psychical act of observation, and we may say that the transition from the 'possible' to the 'actual' takes place as soon as the interaction of the object with the measuring device, and thereby with the rest of the world, has come into play; it is not connected with the act of registration of the result by the mind of the observer. The discontinuous change in the probability function, however, takes place with the act of registration, because it is the discontinuous change of our knowledge in the instant of registration that has its image in the discontinuous change of the probability function." [24, p. 54]

In order to make sense of the jump, Heisenberg recovered potentiality for physics through the hylomorphic Aristotelian scheme.

"In the experiments about atomic events we have to do with things and facts, with phenomena that are just as real as any phenomena in daily life. But the atoms or the elementary particles themselves are not as real; they form a world of potentialities or possibilities rather than one of things or facts." [24, p. 160]

Continuing Heisenberg's considerations in the new physics, Constantin Piron has been one of the leading figures in developing the notion of potentiality within the logical structure of quantum mechanics [33, 34, 35]. The Geneva approach to quantum logic attempts to consider quantum physics as related to the realms of actuality and potentiality analogously to classical physics. According to the Geneva school, both in classical and quantum physics measurements will provoke fundamental changes of the state of the system. What is special for a classical system, is that 'observables' can be described by functions on the state space. This is the main reason that a measurement corresponding to such an observable can be left out of the description of the theory 'in case one is not interested in the change of state provoked by the measurement', but 'only interested in the values of the observables'. It is in this respect that the situation is very different for a quantum system. Observables can also be described, as projection valued measures on the Hilbert space, but 'no definite values can be attributed to such a specific observable for a substantial part of the states of the system'. For a quantum system, contrary to a classical system, it is not true that 'either a property or its negation is actual'. A physical property, never mind whether a classical or quantum one, is specified as what corresponds to a set of definite experimental projects [48]. A *definite experimental project* (DEP) is an experimental procedure (in fact, an equivalence class of experimental procedures) consisting in a list of actions and a rule that specifies in advance what has to be considered as a *positive* result, in correspondence with the *yes* answer to a dichotomic question. Each DEP tests a property. A given DEP is called *certain* (correspondingly, a dichotomic question is called *true*) if it is sure that the positive response would be obtained when the experiment is performed or, more precisely, in case that whenever the system is placed in a measurement situation then it produces certain definite phenomenon to happen. A physical property is called *actual* in case the DEPs which test it are certain and it is called *potential* otherwise. Whether a property is actual or potential depends on the state in which one considers the system to be. Though in this approach both actuality and potentiality are considered as modes of being, actual properties are considered as attributes that

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exist, as elements of (EPR) physical reality, while potential properties are not conceived as existing in the same way as real ones. They are thought as *possibilities* with respect to actualization, because potential properties may be actualized due to some change in the state of the system. In this case the superposition provides a measure —given by the real numbers which appear in the same term as the state— over the irrational potential properties which could become actual in a given situation. Thus, potentiality, as in the classical physical sense, can be regarded as *irrational potentiality*, as referring to a future in which a given property can become actual.

Also closely related to the development of Heisenberg in terms of potentialities stands the development of Margenau and Popper in terms of latencies, propensities or dispositions. As recalled by Suárez [47], Margenau was the first to introduce in 1954 a dispositional idea in terms of what he called *latencies*. In Margenau's interpretation the probabilities are given an objective reading and understood as describing tendencies of latent observables to take on different values in different contexts [28]. Later, Karl Popper [36], followed by Nicholas Maxwell [29], proposed a propensity interpretation of probability. Quantum reality was then characterized by irreducibly probabilistic real propensity (propensity waves or propensitons).[10] More recently, Mauricio Suárez has put forward a new interpretation in which the quantum propensity is intrinsic to the quantum system and it is only the manifestation of the property that depends on the context [46, 47]. Mauro Dorato has also advanced a dispositional approach towards the GRW theory [18, 19]. The GRW theory after their creators: Ghirardi, Grimmini and Weber [23] is a dynamical reduction model of non-relativistic QM which modifies the linearity of Schrödinger's equation.

However, these approaches based in the final cause face also difficulties:

> "Collapses constitute a process of evolution that conflicts with the evolution governed by the Schrödinger equation. And this raises the question of exactly when during the measurement process such a collapse could take place or, in other words, of when the Schrödinger equa-

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[10]The realist position of Popper seemed in this respect much more radical than the interpretation of Heisneberg in terms of potentia. Heisenberg [24, pp. 67-69] seemed to remain within a subjectivist definition of such potentia: "Such a probability function [i.e. the statistical algorithm of quantum theory] combines objective and subjective elements. It contains statements on possibilities, or better tendencies ('potentiae' in Aristotelian philosophy), and such statements are completely objective, they don't depend on any observer the passage from the 'possible' to the real takes place during the act of observation". This was something Popper was clearly against.

tion is suspended. This question has become very urgent in the last couple of decades, during which sophisticated experiments have clearly demonstrated that in interaction processes on the sub-microscopic, microscopic and mesoscopic scales collapses are never encountered." [15, p. 120]

4.2 Non-Collapse Solutions and the Return of the Efficient Cause

Put in a nutshell, non-collpase interpretations attempt to "restore a classical way of thinking about *what there is.*" [2, p. 74] And what there is, is a definite valued set of properties constituting an *actual state of affairs.* There is one single realm of existence: actuality. Possibility —as in classical physics— in only epistemic, reflecting our ignorance about what there is. Non-collapse interpretations deny the existence of a collapse during measurement and claim —in different ways— that the quantum superposition also expresses —at least partly— the actual realm.

Many worlds interpretation (MWI) of QM is one of the well known non-collapse interpretations which has become an important line of investigation within the foundations of quantum theory domain. It is considered to be a direct conclusion from Everett's first proposal in terms of 'relative states' [20]. Everett's idea was to let QM find its own interpretation, making justice to the symmetries inherent in the Hilbert space formalism in a simple and convincing way [11]. The solution proposed to the measurement problem is provided by assuming that each one of the terms in the superposition is *actual* in its own correspondent world. Thus, it is not only the single value which we see in 'our world' which gets actualized but rather, that a branching of worlds takes place in every measurement, giving rise to a multiplicity of worlds with their corresponding actual values. The possible splits of the worlds are determined by the laws of QM. In this case, there is no need to conceptually distinguish between possible and actual because each state is actual inside its own branch and the **EEL** is maintained in each world. As remarked by Everett [21, p. 146-147] himself: "The whole issue of the transition from 'possible' to 'actual' is taken care of in the theory in a very simple way —there is no such transition, nor is such a transition necessary for the theory to be in accord with our experience. From the viewpoint of the theory all elements of a superposition (all 'branches') are 'actual', none any more 'real' than the rest."

Another well known non-collapse interpretation is the so called modal in-

terpretation (MI) of QM. This approach states that superpositions remain always intact, independent of the result of the actual observation.[11] One might say that the **EEL** is here accepted only in one direction, implying that given a state that is an eigenstate there is a definite value of the corresponding magnitude, i.e. its eigenvalue, but not the other way around. "In modal interpretations the state is not updated if a certain state of affairs becomes actual. The non-actualized possibilities are not removed from the description of a system and this state therefore codifies not only what is presently actual but also what was presently possible. These non-actualized possibilities can, as a consequence, in principle still affect the course of later events." [51, p. 295] There are thus, within MI, two realms or levels given by the possible and the actual.[12] The passage from the possible to the actual is given through different interpretational rules, depending on the version of the MI [51]. Leaving aside van Fraassen's empiricist stance according to which: *modalities are in our theories, not in the world*;[13] there are several realistic MI in which the ideal of an actual state of affairs is recovered, as a consequence "the probabilities occurring in the modal interpretation have the same status as classical probabilities and have the usual classical interpretations." [14, p. 15] While Dieks earlier version assumes the existence of one single actual property, the Bohmian versions of Bub and Bacciagaluppi and Dickson assume the existence of a set of actual definite valued properties [6, 3]. In both cases possibility remains epistemic and only actuality is regarded as real. This is why MI were called by Bacciagaluppi a hidden variable theory [2]. As explained by Dieks:

"In our search for definite-valued observables it is possible to include interpretations like the Bohm interpretation if we allow for the possibility that there is a preferred observable R that is always definite, for all quantum states (in the Bohm theory position plays this role).

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[11]Van Fraassen discusses the problems of the collapse of the quantum wave function in [49], section 7.3. See also [12]. Dieks [13, p. 182] argues that: "[...] there is no need for the projection postulate. On the theoretical level the full superposition of states is always maintained, and the time evolution is unitary. One could say that the 'projection' has been shifted from the level of the theoretical formalism to the semantics: it is only the empirical interpretation of the superposition that the component terms sometimes, and to some extent, receive an independent status."

[12]These levels are explicitly formally accounted for in both van Fraasen and Dieks MI. While van Fraassen distinguishes between the 'dynamical states' and the 'value states', Dieks and Vermaas consider a distinction between 'physical states' and 'mathematical states' [52].

[13]Dieks has taken a stance in favor of an empiricist position regarding modality [15].

The situation in which no privileged observable exists then becomes a special case." [14, p. 6]

Since the recovery of an actual state of affairs plays a major role within some of the realist versions of the MI the connection to MWI might be also regarded as quite direct:[14]

"There is perfect equivalence [to the MI] in the sense that the many-worlds interpretation is defined by the condition that each element of the measure space corresponds to an actual states of affairs, whereas the probabilistic alternative is defined by the condition that each element may correspond to the one actual (but unspecified) state of affairs." [14, p. 17]

5 Inverting the Measurement Problem: Powers and the Immanent Cause

Due to his choice of a teleological scheme —based on irrational potentiality and supplemented by the final cause— Aristotle had closed the door to a radical development of potentiality in terms of a mode of existence. As remarked by Wolfgang Pauli:

"Aristotle [...] created the important concept of *potential being* and applied it to *hyle*. [...] This is where an important differentiation in scientific thinking came in. Aristotle's further statements on matter cannot really be applied in physics, and it seems to me that much of the confusion in Aristotle stems from the fact that being by far the less able thinker, he was completely overwhelmed by Plato. He was not able to fully carry out his intention to grasp the *potential*, and his endeavors became bogged down in early stages." [32, p. 93]

This choice, of relegating the potential realm to the actual, still resonates in both collapse and non-collapse interpretations discussed in the previous section. Both solutions have concentrated their efforts in justifying the already known actual realm instead of investigating potentialities as an independent mode of existence: by considering potentiality, but focussing on the process of actualization —going back to Aristotle's hylomorphic scheme—, or by

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[14]Private discussion with Prof. Dr. Dieks, April 2013, Rio de Janeiro.

eliminating completely the potential realm and providing an actualist account of superpositions —going back to classical physics and the Laplacian myth. The measurement problem provides in itself already the limits of its own solution. The question implies a focus on actual observation accepting implicitly that it is only actuality which reflects the real. Instead, we attempt to turn upside-down the questioning and produce what we call an '*inversion* of the measurement problem'. The question that interest us is not: how do we justify actuality in QM? But rather: What is the physical concept which could allow us to think about a quantum superposition, in analogous way in which the notion of physical object moving in space-time is used to interpret a mathematical point in Γ evolving according to the equation of motion. Physical entities exist in the mode of being of actuality. But what would it be the mode of existence of the concept we are seeking for QM? Since the many approaches based on actuality have failed until now to provide a coherent interpretation of the theory, we regard as an interesting attempt to concentrate our efforts in the development of a different and independent mode of existence to that of actuality.

Our stance is that physics is necessarily related to a specific mathematical and conceptual representation.[15] New physical theories are born with the creation of new concepts, new mathematical formalisms and new experience. There is no primacy of one of the elements over the other, but rather a tight interrelation constantly growing in different directions. If we accept this standpoint, the interpretational question regarding QM is not, how does it collapse or evolve into classical mechanics, but rather, how do we find new concepts which match the orthodox formulation and allow us to think about quantum experience in a coherent manner. A strategy we have followed is to consider QM as describing "things" —mathematically described by quantum superpositions— which exist in a different realm to that of actuality. We have proposed to develop such a realm taking into account Aristotle's rational potentiality, but in order to make clear the distance in between this concept and that of Aristotle we have named it: *ontological potentiality*. We claim that it is empirical data itself which points in the direction of the existence of a potential realm independent of actuality. Though an adequate concept is still missing to characterize quantum superpositions, it is the physical experience done today in laboratories which points in the direction of considering quantum superpositions as ontologically robust. We expect that ontological potentiality will allow us to develop a conceptual

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[15]For an analysis regarding this specific point see [40, 41].

scheme that interprets quantum superpositions in a new light, providing at the same time new insights to account for the non-actualized potential level. The independence of both realms does not imply a complete denial of the relation between the potential and the actual, but rather, the possibility to turn upside-down the gnoseological relation between the actual and the potential. In our scheme it is not the potential which needs to explain the actual, but rather the actual which can explain the potential.

But what are the "things" of which QM is talking about? We propose to consider superpositions as representing a multiplicity of *powers*, each of them with a given *potentia*. A power can be thought to exist within the realm of ontological potentiality, completely independent of the actual realm. In fact, our strategy will be to use such non-teleological powers in order to provide a representation of the main elements which seem to constitute the formal structure of a superposition, namely, *its existence regardless of the effectuation of one of its terms*, as shown, for example, by the interference of different possibilities in *welcher-weg* type experiments [8, 27], *its non-standard route to actuality*, as explicitly shown by the MKS theorem [17, 42], *its reference to contradictory properties*, as in Schrödinger cat states [31], and *its non-classical interference with itself and with other superpositions*, used today within the latest technical developments in quantum information processing [7]. Once we have taken seriously the existence of potentiality as independent of actuality we can also bring into stage the idea of *potential effectuations*; i.e., effectuations which take place independently of *actual effectuations*. A power can have an actual effectuation, which is the way we have learnt about them, but it can also have a potential effectuation, which is what physicist in laboratories are learning about today.[16] This idea breaks down the teleological relation provided by the *final cause* between the potential and the actual and supports the deconstruction of the idea that: actuality = reality, opening at the same time the door to the consideration of something that exists which is not necessarily actual —an ontology of powers which needs to be considered on equal footing to the ontology of entities in classical physics.

However, since QM itself was born from certain specific set of actualities, we still need to build a bridge between the actual and the potential, i.e. we also need to provide an answer to the measurement problem. But going now back to it, due to our new scheme, we need to be much more specific. Thus,

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[16]We attempt to investigate in a future work the understanding of present experiments in terms of powers and potential effectuations.

the following question rises: what is the relation between powers and actual effectuations? It is the *immanent cause*[17] which allows us to retain powers independently of actual effectuations. The immanent cause allows for the expression of effects remaining both in the effects and its cause. It does not only remain in itself in order to produce, but also, that which it produces stays within. Thus, in its production of effects the potential does not deteriorate by becoming actual —as in the case of the hylomorphic scheme. Applied to the superposition the immanent cause allows for the expression of actual results without affecting in any way the superposition itself. Actual results become single effectuations, singularities which express the superposition in the actual mode of existence, while superpositions remain evolving deterministically —according to the Schrödinger equation— in the potential mode of existence, even interacting with other superpositions and producing new potential effectuations. Some of these aspects might reminds us of some main features of possibility within the MI itself, now read from an ontological perspective.[18]

6   Conclusion

We have criticized both actualists and hylomorphic solutions for grounding their questioning in the justification of "common sense" experience, leaving aside the signs which QM has placed for more than one century about the existence of a different realm to that of actuality. However, our proposal combines elements of both collapse and non-collapse solutions. On the one hand, like in collapse solutions, we recover the notion of potentiality; but unlike them, we consider potentiality as a mode of existence independent to actuality and change the link between the potential and the actual, leaving aside the final cause and introducing in its place the immanent cause. On the other hand, like in non-collapse solutions, we do not conceive **PP** as an actual physical interaction which destroys all terms in the superposition except the one observed; rather we understand **PP** as an expression —articulated by the immanent cause— of the potential level within actuality. Breaking down the causal teleological relation between the potential and the actual realms means to place the potential in a completely different

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[17]The immanent cause goes back to the discussion regarding God and its attributes. It was Spinoza who might have taken it to its maximum expression in the *Ethics*, also contained in the maxim: *Deus sive Natura*. See for example: [30].

[18]We attempt to analyze this path in more detail in future works.

ontological ground. This does not mean the elimination of the actual realm, but rather, a different and more restricted understanding of it. Ontological potentiality and the immanent cause can offer us a new original path to investigate quantum superpositions and try to understand the relation between the quantum mechanical formalism and experience.

Acknowledgments

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