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Quantum propensities

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Abstract

This paper reviews four attempts throughout the history of quantum mechanics to explicitly employ dispositional notions in order to solve the quantum paradoxes, namely: Margenau's *latencies*, Heisenberg's *potentialities*, Maxwell's *propensitons*, and the recent *selective propensities* interpretation of quantum mechanics. Difficulties and challenges are raised for all of them, and it is concluded that the selective propensities approach nicely encompasses the virtues of its predecessors. Finally, some strategies are discussed for reading similar dispositional notions into two other well-known interpretations of quantum mechanics, namely the GRW interpretation and Bohmian mechanics.

Keywords: Propensities; Dispositions; Quantum mechanics; Problem of measurement

1. Introduction

The history of dispositional properties in quantum mechanics is arguably as long as the history of quantum mechanics itself. A dispositional account of quantum properties is arguably implicit in the early quantum theory, for instance in Bohr's model of the atom, since transitions between quantum orbitals can be described as stochastic processes that *bring about* certain values of quantum properties with certain probabilities. Similarly, on the orthodox Copenhagen interpretation, measurements do not reveal pre-existent values of physical quantities, but *bring about* values with some well-defined probability. Then, in addition, starting in the 1950s there has been a succession of explicit attempts to employ

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dispositional notions in order to understand quantum mechanics. They include Margenau's (1954) latency interpretation, Heisenberg's (1958) appeal to Aristotelian potentialities, Maxwell's (1988, 2004) propensiton theory and my own recent defence of a dispositional reading of Arthur Fine's selective interactions (Fine, 1987; Suárez, 2004b).

In this paper I describe and compare these four interpretations of quantum mechanics and I contend that all their virtues are appropriately subsumed under the latter selective propensities view. I then point out some reasons for thinking that similar dispositional notions might also be appropriate for other mainstream interpretations or versions of quantum mechanics—even if they have not made explicit use of dispositional notions before—such as the Ghirardi–Rimini–Weber (GRW) *collapse* interpretation, and Bohmian mechanics.

The paradigmatic *interpretational* question of quantum mechanics may be taken to be a question about the general interpretation of superposed states (see e.g. Albert, 1992, Chapter 1): *What does it mean—with respect to the property represented by the observable Q—for a quantum system to be in state Ψ that is not an eigenstate of the Hermitian operator corresponding to Q*?[1] Different interpretations of quantum mechanics can be fruitfully distinguished in terms of the answers they provide to this question. The views described here vary greatly in their details, their complexity and their ontological assumptions, but their answer to the paradigmatic interpretational question is essentially the same and it includes a reference to some among the nexus of dispositional notions. We may summarise it as follows: *It means that the system possesses the disposition*, *tendency*, or *propensity*, *to exhibit a particular value of Q if Q is measured on a system in state Ψ*. It is my purpose in this paper to argue that this answer to the question remains viable in spite of past failures to articulate it convincingly.[2]

2. Margenau's *latency* interpretation

In an excellent pioneering article published in 1954 Margenau argued in favour of an interpretation of quantum observables as dispositional physical quantities, which he called *latencies*. The argument proceeded in two stages. First, negatively, Margenau argued against both Bohm's theory and the Copenhagen interpretation (Margenau, 1954, pp. 8–9). In particular he criticised the Copenhagen interpretation for its supposedly dualistic features—for asserting that particles have positions at all times, yet we are unavoidably ignorant of what these are. In other words, he assumed that the Copenhagen tradition takes a subjective reading of the quantum probabilities and the uncertainty relations, and that it postulates an essential role for consciousness and the observer, and criticised both assumptions.[3]

By contrast Margenau proposed a "third-way" interpretation of quantum mechanics that treads an intermediate course, whereby the probabilities are given an objective

[1]Throughout the essay I refer indistinctly to physical observables and Hermitian operators that represent them. It obviously does not follow that all Hermitian operators represent physically meaningful properties. See also Section 7 for an application of dispositions to Bohm's theory, where notoriously Hermitian operators play a limited role.

[2]It will also be important to characterise these notions precisely, and I will attempt to do so in Section 6. In the meantime it suffices to say that I will take "disposition" to be an umbrella term that encompasses all the others, such as capacity, tendency or propensity.

[3]It is debatable to what extent the Copenhagen interpretation can be historically identified with this corpus of ideas. See Howard (2004) for an excellent discussion.

reading, and they are understood as describing tendencies—more precisely: the tendencies of latent observables to take on different values in different experimental contexts. Here is an extensive quote (Margenau, 1954, p. 10):

> The contrast, or at any rate the difference, is now between [. . .] possessed and latent observables. Possessed are those, like mass and charge of an electron, whose values are "intrinsic", do not vary except in a continuous manner, as for examples the mass does with changing velocity. The others are quantized, have eigenvalues, are subject to the uncertainty principle, manifest themselves as clearly present only upon measurement. I believe that they are "not always there", that they take on values when an act of measurement, a perception, forces them out of indiscriminacy or latency.

Margenau's "third" or "latency" interpretation is extraordinarily prescient and insightful in many respects. It ought to be a classic source, if not the classic reference, for all dispositional accounts of quantum mechanics. Yet it is often ignored, even by the proponents of dispositional accounts themselves.[4] For instance, Heisenberg's late 1950s writings (reviewed in Section 3), and Popper's well-known writings on the propensity interpretation of quantum probabilities, both fail to discuss Margenau's views.[5]

Margenau's *latency* interpretation provides a basic *template* for dispositional accounts. Suppose that state Ψ can be written as a linear combination $\Psi = \sum_n c_n |v_n\rangle$ of the eigenstates v_n of the *latent* observable represented by Q with spectral decomposition given by $Q = \sum_n a_n |v_n\rangle\langle v_n|$. We may then answer the paradigmatic interpretational question as follows: *a system is in state* $\mathbf{\Psi}$ *if and only if it has on a measurement of* $\boldsymbol{Q}$ *the disposition to manifest eigenvalue* $\boldsymbol{a}_i$ *with probability* $|\boldsymbol{c}_i|^2$. I will argue throughout this paper in favour of this basic *template* as the core of any appropriate dispositional account of quantum mechanics.

However, Margenau's third interpretation goes beyond the basic *template* in some unhelpful ways. It does not distinguish between the possession of a value of a physical property, and the possession of the property itself—a distinction that makes no sense for categorical properties, but is essential in order to understand dispositional property ascriptions.[6] A failure to draw this distinction leads Margenau to link inappropriately the

[4]A notable exception is the distinguished British philosopher of physics Redhead (1987, p. 49), who mentions Margenau's view favourably.

[5]It is hard to believe that these authors did not know of Margenau's contributions. Margenau was a well-known figure in the post-war period: he was Professor of Physics and Natural Philosophy at Yale, a member of the American Academy or Arts and Sciences, President of the American Association for the Philosophy of Science, and a prominent defender of the need for philosophical reflection on physics.

[6]The metaphysical literature on dispositions tends to make a more nuanced distinction between the dispositional property possessed and the property manifested in the exercise of the disposition (e.g. Mumford, 1998, Chapter 4). We could then refer to e.g. "spinable" as the dispositional property that gets manifested, in the appropriate circumstances, in the possession of the categorical property "spin". However, this cumbersome double terminology will be avoided here because (a) physicists do not distinguish these two properties, and (b) I will argue following Mellor (1971) that quantum propensities are displayed not in the possession of a particular value of the manifestation property, but in a probability distribution over the values of the corresponding manifestation property. Hence the cumbersome distinction can be avoided as long as we admit that a dispositional property may be possessed in the absence of any value of this property. See Suárez (2004a, 2004b, pp. 244) for further discussion. The idea that a property may be ascribed without a value has been used in the philosophy of quantum mechanics before, for instance by Hilary Putnam in his celebrated work on quantum logic. But a reader

actualisation of latent properties with their existence. In other words, the act of measurement not only brings into existence the value of the latent property in question, but the latent property itself. So in the absence of a measurement of position, for instance, an electron has no value of position, and as a consequence it has no position at all.

Let me first provide a diagnosis of the motivating sources of Margenau's conflation. One reason why Margenau is led this way is a prior conceptual conflation of three terms ("property", "physical quantity" and "observable") that ought to be kept distinct. We would nowadays take "observable" to be synonymous with a quantum property—some of these "properties" might be dispositional, others might be categorical, and we would only denote the latter as "physical quantities". But failing to distinguish them in this way, Margenau identifies all properties with physical quantities and is thus forced to conflate observables and physical quantities. It then follows that if an observable lacks a value (i.e. if it is not a physical quantity) it fails to correspond to a real property. So Margenau is now led to require that a property can only obtain if it is actualised (has a value); i.e. if it corresponds to a physical quantity. Hence Margenau is forced to discard what I would argue is the most natural dispositional account, namely: that systems *possess* their dispositional properties at all times—in a realist sense of the term, as applied to dispositions—without thereby implying that their values are actualised, or manifested, at all times. (In the terminology just developed: an observable that corresponds to a dispositional property may at a given time lack a value and hence fail to correspond to a physical quantity).

Margenau's conflation of properties and values has two pernicious consequences for his interpretation of quantum mechanics. First, any presumed advantages over other interpretations in solving the quantum paradoxes disappear. And second, new additional problems related to the identity of quantum objects are imported into the picture. I will discuss them both in turn.

The first consequence becomes clearer in the context of the measurement problem. According to the model of measurement provided by the quantum formalism, if we let our initial quantum system interact with a macroscopic measurement device we obtain what is known as macroscopic superposition infection: the composite (system + device) goes into a superposition. Formally, the state of the composite at the end of the interaction looks like this: $\Psi = \sum_{n,m} c_{nm} v_n \otimes \mu_m$, where μ_m are the eigenstates of the pointer position observable with corresponding eigenvalues $\boldsymbol{a}'_m$ (and so $\boldsymbol{c}_{nm} = \boldsymbol{a}_n \boldsymbol{a}'_m$). The challenge is then to predict theoretically that in this state the macroscopic measurement device pointer will point to some value or other (sometimes known as the problem of *objectification* of the pointer position). This is compounded by the fact that, on the standard interpretational rule for quantum states (the eigenstate/eigenvalue or e/e link), a system in a superposition of eigenstates of an operator has no value of the property represented by that operator. Hence the pointer takes no values in the final state of the composite. To resolve this problem a dispositional account must hold its nerve and apply the basic template firmly: *a system is in state* $\boldsymbol{\Psi}$ *if and only if it has on a measurement of* $\boldsymbol{O}$ *the disposition to manifest eigenvalue* $\boldsymbol{a}_i \boldsymbol{a}'_j$ *with probability* $|\boldsymbol{c}_{ij}|^2$. In other words, a dispositional account must without reservation ascribe a property over and above those dictated by the (e/e link), since a

(*footnote continued*)
for whom this notion is cause of mental spam can throughout the ensuing discussion substitute in the more standard dual adscription of a disposition and its manifestation property without any loss of generality.

property is ascribed without there being a value that it takes (or in our adopted terminology: a *dispositional property* is ascribed without ascribing a corresponding *physical quantity*). But Margenau's conflation leaves no conceptual room left to break the (e/e link) in this way.[7]

On the contrary, on Margenau's interpretation the latent observable is not present ("manifested as clearly present") unless upon measurement. It follows that the pointer position observable is not "present" unless the measurement device is subject to its own measurement interaction—i.e. a second-order interaction—in order to find out the dispositions exhibited by the composite system in state $\mathbf{\Psi}$; and this way the problem just seems to recur indefinitely. There is no way to break the impasse simply by claiming that the system has some disposition that gets actualised at the conclusion of the measurement interaction—since (i) on Margenau's reading the system does not have a latent property unless the property is being measured, and (ii) no pointer position observable would get actualised in any case unless a third measurement apparatus is brought into the picture.

But in fact the conflation of properties and values brings in added complications, as Margenau himself noticed—issues of particle identity arise: suppose that an electron has a number of possessed properties ("mass", "charge") and a number of latent ones ("spin"). For any particular electron the possessed properties remain constant but not so the latent ones. These jump in and out of existence in accordance with measurement situations. Note that this is not to say that the values of a property of an entity change over time (a triviality that does not threaten the identity of the entity) but rather that the set of the entity's defining properties changes. As Margenau himself aptly writes: "It may be that this latency affects even the identity of an electron, that the electron is not the same entity with equal intrinsic observables at different times" (Margenau, 1954, p. 10). This is not *prima facie* good news: the dissolution of system's identities seems too high a price to pay for a coherent interpretation of quantum mechanics.

3. Heisenberg's Aristotelian *potentialities*

In 1958, soon after Margenau's proposal, Heisenberg published *Physics and Philosophy*, his best known philosophical reflection on quantum mechanics. The book is often celebrated as an exposition of a standard version of the Copenhagen interpretation. It is certainly explicit in its defence of that view—Chapter 3 is even entitled "The Copenhagen Interpretation of Quantum Theory". But a close reading of the book reveals a very complex mixture of interpretational elements, only some compatible with what we nowadays would identify as a Copenhagen interpretation. A commitment to reading the quantum probabilities at least in part in terms of Aristotelian potentialities stands out among the elements apparently alien to the Copenhagen view: "The probability function combines objective and subjective elements. It contains statements about possibilities or better tendencies ("potentia" in Aristotelian philosophy), and these statements are completely objective, they do not depend on any observer; and it contains statements

[7]To be coherent all dispositional accounts of quantum mechanics must have the courage to similarly break the (e/e link). It is worth noting that this brings dispositional accounts somewhat in line with modal interpretations, which notoriously deny the (e/e link). But there is a crucial difference: while modal interpretations ascribe values to properties even though not eigenvalues, propensity views ascribe properties but without values. This is an altogether different way of breaking the (e/e link) since it rejects a common presupposition underlying the (e/e link), without denying the letter of the (e/e link). See Suárez (2004b, Section 7) for discussion.

about our knowledge of the system, which of course are subjective in so far as they may be different for different observers'' (Heisenberg, 1958, p. 53).

Heisenberg is not very clear about how precisely these objective and subjective elements combine. The very locution that a probability function ''contains statements'' is puzzling from the standpoint of contemporary philosophical treatments of probability. Perhaps the most plausible interpretation of these cryptic passages in Heisenberg's writings can be obtained by replacing ''contains'' with ''implies'', since it does not seem implausible to claim that the probability function implies statements about possibilities or tendencies. But again Heisenberg is not very explicit about whether the quantum probability distributions represent subjective degrees of belief (and thus imply statements about our knowledge), or objective frequencies or propensities (thus implying statements about matters of fact independent of our knowledge).

Sometimes Heisenberg comes close to asserting a version of David Lewis' *Principal Principle*, or some other general rule whereby (rational) subjective degrees of belief must follow objective chances when these are known (Lewis, 1980/6). Quantum probabilities may then just measure rational degrees of belief, while pertinently tracking objective chances. This would at least seem to give some substance to Heisenberg's claim that the quantum probabilities imply both statements about our subjective knowledge of the system and statements about the objective potentialities of the system. It also seems close to what Heisenberg aims for in the following paragraph, for example (Heisenberg, 1958, p. 54):

> Therefore, the transition from the 'possible' to the 'actual' takes place during the act of observation [...] 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.

Heisenberg does not provide a detailed model of these Aristotelian 'potentia'. Rather he appeals to them as a brute explanation of the discontinuous change that measurements bring to the probability function: And, like Margenau, he is also unclear as to whether merely some of quantum systems' properties are dispositional, or the systems themselves fully exist only ''in potentia''.[8]

The appeal to dispositional properties as grounding quantum measurements is one of the two key elements in Heisenberg's otherwise vague discussion. I will argue in Section 5 that the other key element is the sharp distinction he draws between these dispositional properties and the quantum probabilities. For it is clear that for Heisenberg ''potentia'' are not merely an interpretation of quantum probabilities. On the contrary, it has been noted that the relationship between the quantum probabilities and these ''potentia'' is rather subtle on Heisenberg's view. The selective-propensity view that I will develop in Section 5

[8]For instance, when he writes (Heisenberg, 1958, p. 160): ''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''.

will also essentially distinguish quantum probabilities from their underlying dispositions (although I will not follow Heisenberg in accepting a subjective interpretation of the quantum probabilities). This second key element in Heisenberg's discussion is particularly important in relation to historically misguided attempts to solve the quantum paradoxes by merely *interpreting* the quantum probabilities as propensities—among which Popper's attempt is the paradigm.[9]

4. Maxwell's propensitons

A more recent propensity-based version of quantum mechanics goes by the name *propensiton theory* and has been developed by Maxwell (1988, 2004). Maxwell makes two fundamental claims: a very general philosophical claim about entities and their structure in general, and another, much more concrete claim specifically about quantum mechanical entities. According to the first (claim 1), the nature of an entity is inherently dependent upon the features of its dynamical laws. Maxwell (1988, p. 10) writes: "In speaking of the properties of fundamental physical entities (such as mass, charge, spin) we are in effect speaking of the dynamical laws obeyed by the entities—and vice versa. Thus, if we change our ideas about the nature of dynamical laws we thereby, if we are consistent, change our ideas about the nature of the properties and entities that obey the laws". This statement seems *prima facie* misguided in light of the historical record. For example, there have been different models of the solar system endowed with their own dynamical laws (such as Tycho's, Kepler's, Newton's or Einstein's laws) but agreeing on the essential nature of the planets (size, density, mass, relative distances, etc.). So it does not seem right on the face of it to say that the nature of the objects depends on the laws.

However, Maxwell's meaning is more subtle and is best brought out by his second claim (claim 2): "The quantum world is fundamentally probabilistic in character. That is, the dynamical laws governing the evolution and interaction of the physical objects of the quantum domain are probabilistic and not deterministic" (Maxwell, 1988, p. 10). The second claim importantly qualifies the first: the distinction that matters is that between deterministic and probabilistic laws. Maxwell's more subtle view is then that there are fundamentally only two kinds of entities: probabilistic and deterministic ones. Thus Maxwell would probably be committed to the view that in a model of the solar system with probabilistic laws the planets would just not be the kinds of entities that they are in our (supposedly deterministic) world, and that is regardless the actual form of the deterministic laws governing their dynamics.

So far, however, this remains all rather cryptic. We can unravel the claim by considering the difference between probabilistic and deterministic laws which seems quite clear on either a formal or a modal account. On the formal account, roughly, a law is deterministic if any future state of a system has conditional probability one or zero given the present state of the system: Prob $(S_f|S_p) = 1$ or 0, for any $S_f > S_p$. On the modal account, roughly, a law is deterministic if there is only one possible world described by the law that is

[9]There is no space in this essay to critically review Popper's interpretation—see e.g. Popper (1959). Popper's famous and influential—but fundamentally flawed—attempt to apply a propensity interpretation to the quantum probabilities nowadays gives all propensity interpretations of quantum mechanics an unfairly bad reputation—which makes it hard for those of us working on the topic to get a fair hearing. The interested reader is referred to my discussion in Suárez (2004a, 2004b, Section 8).

compatible with the history of the actual world so far.[10] Given this account of laws, what exactly is the ontological difference between essentially probabilistic and deterministic entities? For instance, in discussing the state of a quantum particle delocalised in space, Maxwell (2004, p. 327) suggests that the spread-out wavefunction in position space entails that quantum entities are not point-particles at all but rather take the form of expanding spheres: ''A very elementary kind of spatially spreading intermittent propensiton is the following. It consists of a sphere, which expands at a steady rate (deterministic evolution) until it touches a second sphere, at which moment the sphere becomes instantaneously a minute sphere, of definite radius, somewhere within the space occupied by the large sphere, probabilistically determined''.

This suggests that on the propensiton theory the wavefunction in position space literally represents the geometric shape of quantum entities, which develop deterministically in time and collapse probabilistically due to inelastic scattering.[11] This is indeed a straightforward way to make true both of Maxwell's fundamental claims. For it is now true—on both the formal and modal accounts of a probabilistic law—that the nature of the entity depends on the law—since its very shape now depends on the probabilistic character of the law. On either view the move from a deterministic to a probabilistic law has an effect on the very geometrical nature of the entity across time: on the formal account the probability that the future state of the sphere-particle be expanded with respect to its present state can no longer be one. And on the modal account there is more than one possible world with differently shaped spheres within them, all consistent with the history of the actual world so far.

The literal interpretation of the wavefunction shows that Maxwell's theory is different from a mere propensity interpretation of probability *à la* Popper, but it brings its own problems. Two sets of difficulties stand out. The first one relates to the ontology invoked, and threatens the propensiton theory with incoherence; while the second problem has to do with the requirement that there be an inelastic creation event of a new particle every time there is a probabilistic collapse. The first problem is straightforward—the postulated process of contraction of the spheres breaks momentum and energy conservation principles, and invoking it in order to solve e.g. the problem of measurement generates as much of a paradox as the paradox that the process was intended to solve in the first place. For now the question becomes: What kind of internal mechanism and what sort of laws govern the sudden contraction of the spheres? The simplest way to get around this problem is to withdraw the claim that the quantum wavefunction literally represents quantum entities—and claim instead that it just represents the probabilistic propensities of point-particles. But such a move fails to provide the desired rationale for claims (1) and (2).

The second set of difficulties is related to the notion, which lies at the heart of the proposal, that a ''contraction'' takes place, according to Maxwell (2004, p. 328) ''whenever, as a result of inelastic interactions between quantum systems, new 'particles', new bound or stationary systems, are created''. According to Maxwell, any measurement interaction will generate some *new* particle, since the localisation of any particle involves the ionisation of an atom, the dissociation of a molecule, etc. The assumption that all measurements are ultimately reducible to position measurements is rather typical in the

[10] Earman (1986) is the locus classicus for definitions of determinism. See particularly Chapter 2.

[11] Thompson (1988) agrees that Maxwell's essentialism about laws entails that the properties of the entities described must be taken literally, including their geometrical shape.

literature, and does not seem particularly problematic. But there are at least two substantial objections to other aspects of the proposal. First, many measurement interactions seem not to result in an inelastic scattering of a *new* particle; particularly salient examples are destructive measurements. And second, whether there are or not such measurement interactions in practice, the insolubility proofs of the measurement problem—as typically formulated in the tensor product Hilbert space formalism—do not describe inelastic scattering creation events. Hence a solution to the paradoxes that demands that all measurement interactions result in inelastic scattering of particles does not solve the theoretical paradox presented by the measurement problem. To solve the problem one could give up the strict requirement of inelastic scattering, and insist instead on some kind of law-like regularity in the collapse of the wavefunction, which will typically result in inelastic scattering in practice. This would turn the propensiton theory into a propensity version of the Ghirardi–Rimini–Weber (GRW) spontaneous collapse theory—which I discuss in the last section of this paper.

5. Selective propensities

On the *selective-propensity* interpretation (Suárez, 2004b) a quantum system possesses a number of dispositional properties, among which are included those responsible for the values of position, momentum, spin and angular momentum. (One might suppose that *all* quantum properties are irreducibly dispositional, although this is not in principle required.) We can represent quantum dispositional properties by means of what Fine (1987) calls the *standard representative*. Consider the following definition of the equivalence class of states relative to a particular observable Q:

> *Q-equivalence class*: $W' \in [W]_Q$ if and only if $\forall W \in [W]_Q$: $\text{Prob}(W, Q) = \text{Prob}(W', Q)$, where $\text{Prob}(W, Q)$ stands for the probability distribution defined by W over all the eigenvalues of Q.

Suppose that Q is a discrete observable of the system with spectral decomposition given by $Q = \sum_n a_n |v_n\rangle\langle v_n| = \sum_n a_n P_n$, where $P_n = |v_n\rangle\langle v_n|$. Consider then a system in a state $\psi = \sum_n c_n |v_n\rangle$, a linear superposition of eigenstates of the observable Q of the system. This state too defines an equivalence class with respect to the observable Q, namely $[P_\psi]_Q$. Following Fine, we can then construct the *standard representative* $W(Q)$ of the equivalence class $[P_\psi]_Q$ as follows:

> *Standard representative*: $W(Q) = \sum_n \text{Tr}\,(P_\psi P_n) W_n$, where $W_n = P_n/\text{Tr}(P_n)$.

$W(Q)$ is a mixed state: A weighed sum of projectors corresponding to Q's eigenstates. It is thus possible to uniquely derive a mixed state $W(Q)$ as the standard representative of the class of states that are statistically indistinguishable from the pure state ψ with respect to a particular observable Q. Now, the *selective-propensity* interpretation claims that the standard representative $W(Q)$, corresponding to the observable defined over the Hilbert space of a system in the state ψ, is a representation of the dispositional property Q possessed by the system. It is thus possible to make the following claim: *For a given system in a state ψ, if ψ is not an eigenstate of a given observable Q of the system, then $W(Q)$ represents precisely the dispositional property Q of the system*. The set S_ψ of all such states $W(Q)$, corresponding to each well-defined observable Q of the system, is the *propensity* state of the system, since it is a full and explicit list of every one of its dispositional

properties. The full state of the system is then $\{S_\psi, P_\psi, v_\psi\}$: the conjunction of the propensity state S_ψ, the dynamical state P_ψ and the value state v_ψ prescribed by the (e/e link) at any given time. Thus the full state changes indeterministically in a measurement interaction that measures Q on the system, while the standard representative $W(Q)$ is subject only to Schrödinger-like evolution.

I have expounded on the details of the selective-propensity interpretation elsewhere. Here I just would like to defend the following claim: the selective-propensity interpretation embodies the main virtues of its predecessors in the history of dispositional accounts of quantum mechanics, while avoiding their defects. The argument for this conclusion will have four stages. First, I point out that the selective-propensity interpretation, unlike Margenau's latencies and Heisenberg's "potentia" distinguishes neatly between systems and properties. Second, I show that unlike Maxwell's propensiton theory, the selective-propensity view does not entail that the nature of systems and their properties depends essentially upon their laws. Then I explain how this interpretation draws a sharp distinction between dispositional properties and their manifestations. The former are quantum propensities and they both explain and underlie the latter, which are the objective probability distributions characteristic of quantum mechanics—under no particular interpretation of "objective probability". Finally, I show that the selective-propensity interpretation solves the measurement problem.

Unlike Maxwell's or Margenau's accounts, the *selective-propensity* account introduces no new metaphysics. Systems are conceived in the traditional way, as physical objects endowed with certain properties with changing values over time. The state specifies both the set of well-defined properties of a system and their values at any particular time. The dynamical laws specify the evolution of the state over time, i.e. the evolution of the set of well-defined properties and of their values over time. The selective-propensity account departs from the traditional view, if at all, in postulating that some of these properties are dispositional—i.e. even though they are always possessed by the systems, their values are not always manifested.[12] But the distinction between systems and their properties is never blurred, and consequently no issues of identity arise out of the ascription of propensities.

Neither is the distinction blurred between systems and their dynamical laws. On the selective propensity view systems only undergo probabilistic transitions, thus actualising their "propensities", when they interact with other systems in particular ways that test such propensities (measurement interactions are a salient case). In closed quantum systems, by contrast, all propensities remain non-actualised. Hence the selective-propensity view explains the emergence of the classical regime by assuming that quantum systems are typically open systems, constantly interacting with the environment. This is the standard assumption in decoherence accounts too, but it is questionable whether these accounts actually bring about the classical realm, since they cannot transform a pure state into a mixture in the way required for definite values—this is another way to say that decoherence approaches cannot solve the problem of measurement even in their own terms (Maudlin, 1995, pp. 9–10). The effect of the selective-propensity view is in this regard closer to the more successful treatments of measurement within the quantum state diffusion, or continuous stochastic collapse approaches, since it effectively provides the right mixed state at the end of the interaction. It is just that on the selective-propensity

[12] I say "if at all" since I am not convinced that there are no legitimate dispositional readings of the properties of classical mechanics, electromagnetism, thermodynamics, etc. For discussion see Lange (2002, Chapter 3).

view, this is achieved without having to replace the Schrödinger equation with a non-linear version, but via its characteristic denial of the (e/e link).[13]

On the *selective-propensity* view the systems' possession of its dispositional properties does not depend upon the character of the laws. A system can possess exactly the same propensities whether it is closed (in which case the propensities cannot be actualised) or open (and hence subject to probabilistic 'actualisation' or 'collapse' of its propensities). It is not the possession of the propensity but its manifestation that turns on the character of the interaction. The type of entity that is endowed with these properties does not itself depend upon the type of interaction that takes place. Thus the selective-propensity view rejects the idea defended by Maxwell that the shape of the quantum system is literally as represented by the wavefunction—e.g. an expanding sphere. Instead on the selective-propensity view the quantum state is an economical representation of the system's dispositional properties, including its position. There is no need to picture the particle in any particular way in between measurements of position; and there is concomitantly no need to avoid the point-particle representation of quantum systems at all times.

Finally, the *selective-propensity* view solves the measurement problem in a very elegant and natural way.[14] It does so by supposing that every measurement of a propensity Q of a system is an interaction of a measurement device with the system that tests only that particular property $W(Q)$ of the system. Since each propensity is represented by the corresponding standard representative $W(Q)$, we can represent the measurement interaction as the Schrödinger evolution of the composite: $W(Q) \otimes W(A) \rightarrow UW(Q) \otimes W(A)U^{-1}$. The result of this interaction is a mixture over the appropriate eigenspaces of the pointer position observable $(I \otimes A) : W^{f}_{Q+A} = U(\sum_n (\mathrm{Tr}\, \psi P_n) W_n \otimes W_A)U^{-1} = \sum_{nm} \eta_{nm}(t) P_{[\beta nn]}$, which is a mixture over pure states, namely projectors onto the eigenspaces of $(I \otimes A)$. Hence the interaction represents the actualisation of the propensity under test, and the resulting state prescribes the probability distribution over the eigenvalues of the pointer position observable that displays the propensity, since each $P_{[\beta nn]}$ ascribes some value to $(I \otimes A)$ with probability one. (For the details, see Suárez, 2004b, pp. 233–238.) Hence the selective-propensity view can ascribe values to the pointer position at the end of the interaction, thus avoiding the insolubility proofs of the measurement problem.

6. The properties of selective-propensities

I would like to end the exposition of the virtues of the *selective-propensity* view with three remarks regarding the nature of the propensities that it employs. The first remark concerns the distinction between dispositions and propensities. Throughout the paper I have been assuming that the former is a more general notion that encompasses the latter: a propensity is always a *kind* of disposition, but not vice versa. But as a matter of fact there is a more specific use of the term 'disposition' that is (unfortunately in my view) entrenched in the literature. According to this use a disposition is a sure-fire property that is always

[13]From the formal point of view, the key is the replacement of the initial superposed state with the standard representative that describes the dispositional property actually under test. Since the standard representative is always a mixed state, Schrödinger evolution correspondingly yields a mixed state at the end of the interaction.

[14]I take the insolubility proofs to provide a formally complete description of the measurement problem. See Brown (1986) for an elegant description.

manifested if the testing circumstances are right. My use of the term in this paper is different—since I employ the term 'disposition' in the more general sense that covers all the others: tendencies, capacities and propensities. Instead I reserve the term 'deterministic propensity' for a sure-fire disposition. Typically dispositional notions have been analysed in terms of conditionals. In those terms my use of these notions is roughly as follows:

> *Full conditional analysis of dispositions*: Object O possesses disposition D with manifestation M if and only if were O to be tested (under the appropriate circumstances $C_1, C_2, \ldots$) it might M.

I believe that this nicely encompasses all uses of terms such as tendencies, latencies, capacities and propensities. But it is clearly distinct from an entrenched use of "disposition" which is best rendered as "deterministic propensity" in my terminology, as follows:

> *Full conditional analysis of deterministic propensities*: Object O possesses the deterministic propensity D with manifestation M if and only if were O to be tested (under the appropriate circumstances $C_1, C_2, \ldots$) it would definitely M with probability one.

It must be noted that a fully fledged conditional analysis of sure-fire dispositions along the lines of this definition is controversial in any case. Martin (1994) and Bird (1998) in particular have advanced a number of arguments that make it suspect. I do not believe these arguments to be conclusive in the case of fundamental or irreducible dispositions (neither does Bird—see Bird, 2004; Suárez & Bird, 2004), but I need not broach the dispute here, since for my purposes in this paper it is only necessary to assert the left-to-right part of the bi-conditional analysis. My claim is thus not that the conditional statement provides a complete analysis of any dispositional notion, but merely that the ascription of a deterministic propensity entails a conditional:

> *Conditional entailment of deterministic propensities*: *If* object O possesses the deterministic propensity D with manifestation M *then*: were O to be tested (under the appropriate circumstances $C_1, C_2, \ldots$) it would definitely M with probability one.

To illustrate these distinctions consider the paradigmatic case of fragility as a deterministic propensity.[15] It follows on either view that the ascription of fragility to a glass, for instance, entails that were the glass smashed (with sufficient strength, against an appropriately tough surface, etc.) it would break. Or to be even more precise, the statement "this glass is fragile" is true only if a series of conditional statements of the form: "if the glass is thrown (under each of a set of conditions $C_1, C_2, \ldots$ etc.) it would break" are all true. Note that the ascription of fragility does not depend on the truth of the antecedents of these conditional statements (it does not require the actual throwing or smashing of the glass), but on the truth of the conditional itself. The glass is fragile even if it is never smashed; since the possession of fragility does not imply the breakage. The breakage of the

[15] In what follows I ignore for the purposes of analysis the important distinction between measure zero and physical impossibility. A further notion would have to be introduced to account for that—perhaps "sure-fire disposition" could be made to correspond with definite manifestations, while "deterministic propensities" could be reserved for manifestations with probability one, which are not physically necessary. But the distinction, however important and cogent, is not relevant to my discussion here.

glass is rather a contingent manifestation of the fragility of the glass, caused by, or at least explained by, its fragility in the appropriate circumstances.

Let us now turn to propensities in general. A propensity can now be generally defined as a probabilistic disposition, i.e. a dispositional property whose ascription does not imply a conditional with a deterministic clause ("with probability one") in the consequent, but a general probabilistic clause instead ("with probability p"). We may then replace the conditional entailment for deterministic propensities with the following necessary condition on the ascription of propensities:

> *Conditional entailment of propensities*: *If* object O possesses propensity P with manifestation M *then*: were O to be tested (under the appropriate circumstances $C_1, C_2, \ldots$) it would M with probability p ($0 \leqslant p \leqslant 1$).

It then follows that a "deterministic propensity" is just a limiting case of the more general notion of "propensity". For an illustration, consider the often used example of the medical evidence that links the use of tobacco with lung cancer. And suppose, for the sake of argument, that there is indeed a real tendency, with diverse strength in each of us, to contract lung cancer. Such a property would be a propensity since its ascription notoriously does not require the truth of any conditional statement of the type: "if individual X continues smoking 20 cigarettes a day, X will definitely contract lung cancer", but rather a set of statements of the sort: "if X continues to smoke at this rate, the probability that X will contract lung cancer is p". The crucial difference between a propensity and a sure-fire disposition is then that the sure-fire disposition (or deterministic propensity) logically implies its manifestation if the circumstances of the testing are appropriately carried out, while the propensity only entails logically a certain probability p of manifestation, *even if* the circumstances of the testing are right for the manifestation. Under the appropriate circumstances the manifestation of a sure-fire disposition is necessary, while the manifestation of a propensity is only probable.

The second remark is related to the distinction between *single-case* and *long-run* varieties of propensity.[16] According to the *long-run* theory a propensity is a feature of a very large sequence of events generated by identical experimental conditions. The advantage of the long-run theory is that it turns a propensity adscription into an empirical claim testable by means of a repeated experiment: the observed relative frequency must then gradually approximate the propensity adscription. (It is instructive here to think of the case of loaded die, where the relative frequency observed in a very long trial progressively approximates the propensity.) Its disadvantage is that it fails to provide objective single-case probabilities. On this view it makes no sense to speak of the propensity of a single isolated event, in the absence of a sequence that contains it: all single-case probabilities are subjective.

Gillies (2000a, pp. 819–820) defends the long-run theory as the correct interpretation of objective probability in general, and quantum probabilities in particular. But his defence of the long-run theory in the quantum case turns out to depend on a long-run account of experimental probabilities in science in general, and so seems inapplicable as an analysis of the theoretical probabilities provided by quantum mechanics. Gillies thinks that the fact that it is extraordinarily difficult to ever repeat exactly the same scientific experiment

[16] For some excellent reviews of different notions of propensity, as well as a balanced and considerate defence of the long-run theory, see Gillies (2000a, 2000b, Chapter 6).

means that no single case probabilities ever obtain in quantum mechanics. But even if Gillies were right that no objective singular *experimental* probabilities can be introduced for any real laboratory experiment performed on quantum entities, this need not mean that the probabilities as predicted by the theory cannot be objective *and* singular. And in fact on most interpretations of quantum mechanics—with the exception of the largely discredited ensemble interpretation—the quantum state allows us to calculate the probabilities for the different outcomes of a *single* measurement performed just *once* on an *individual* quantum system prepared in that state.

Hence the single-case propensity theory is, in my view, the most likely objective interpretation of quantum probabilities in light of the inadequacies of the ensemble interpretation of quantum mechanics. (There are in turn a number of different versions of the single-case propensity view[17] but, given what follows I do not here need to opt for either.) However, it should be clear that I am not advocating a single-case interpretation of objective probabilities in general, nor of quantum probabilities in particular. The selective-propensity view is not an interpretation of quantum probabilities, but of quantum *mechanics*. It does not address the question "what is the nature of the quantum probabilities", but instead the paradigmatic interpretational question of quantum mechanics, namely: "What does it mean—with respect to the property represented by an observable Q—for a quantum system to be in state Ψ that is not an eigenstate of the observable Q?" In addressing this question the selective-propensity view postulates the existence of propensities as an explanation of the observed probability distributions, *but it does not interpret these distributions in any particular way*.[18]

This leads me to the final comment regarding the nature of the propensities involved in the selective-propensity view. A rightly influential argument against the propensity interpretation of objective probability is known as *Humphrey's Paradox*. It was first noted by Paul Humphreys that conditional probabilities are symmetric but propensities are not, in the following sense (Humphreys, 1985; Salmon, 1979). For a well-defined conditional probability $P(A|B)$, the event B that we are conditionalising upon need not temporally precede the event A. But if B is the propensity of a system to exhibit A, then B must necessarily precede A in time; the propensity ascription seems to make no sense otherwise. Hence *Humphrey's paradox* shows that not all objective probabilities are propensities. But the paradox is only a problem for propensity interpretations of probability, and I have already made it clear that on the selective-propensity view, quantum probabilities are not to be interpreted in any particular way. The point of introducing selective-propensities is not to interpret quantum probabilities but to explain them.[19]

7. Propensities in other interpretations of quantum mechanics

I have stressed the essential explanatory role of that propensities play in a particular interpretation of quantum mechanics. In this final section I would like to sketch out ways

[17]Such as the relevant-conditions theory of Fetzer (1981) and the state of the universe theory of Miller (1994); they differ on the type of conditions that they take to be necessary in order to define a propensity.

[18]Other than by insisting that they are genuine objective chances—and the no-theory theory recently defended by Sober (2005, p. 18) suggests that chances require no interpretation.

[19]The probability distributions of quantum mechanics are explained as the typical displays of the underlying propensities in the appropriate experimental circumstances (Suárez, 2004b). For a general theory of propensities along these lines see Mellor (1971, Chapter 4).

in which similar dispositional notions can be profitably applied to a proper understanding of other versions of quantum mechanics, in particular (a) the GRW collapse theory, and (b) Bohmian mechanics. The claim is part of larger project (so far only a conjecture) to show, more generally, that dispositional notions are consistent with *all* interpretations and versions of quantum mechanics, including for instance Bohr's own distinct version of the Copenhagen interpretation, and many worlds and many minds. But in this paper I only have space to provide the outlines of a defence of the more modest claim that propensity notions are consistent with these two theories.

7.1. GRW collapse interpretations

There is of course a very long history to collapse interpretations of quantum mechanics, going as far back as Von Neumann (1932/1955, Chapter 6 in particular) who famously invoked collapse mechanisms in order to explain the appearance of definite-valued observables as the outcome of measurement procedures—which would be impossible to predict on a standard Schrödinger evolution. Contemporary collapse approaches to quantum mechanics are not exactly interpretations of the quantum theory, since they replace the Schrödinger equation evolution with a non-linear stochastic evolution equation. In this sense they are competitor theories to quantum mechanics, like Bohm's theory. The GRW theory is the best known collapse interpretation of quantum mechanics. It was developed by Giancarlo Ghirardi, Alberto Rimini and Tullio Weber in a number of papers over the 1980s.[20] The GRW theory supposes that systems in quantum states governed by the Schrödinger equation, also undergo sudden and spontaneous state-transitions that instantaneously localise them in physical space.

In this section I will only comment briefly on the original GRW theory. But I believe my conclusions extrapolate rather well to the more sophisticated and plausible models that GRW has given rise to in the last decade or so. In particular further work by Gisin, Pearle and Percival has been crucial in the development of a series of continuous localisation models where the "jumps" in the original GRW are replaced by smoother continuous stochastic evolutions that achieve the desired localisation of the state over a relatively brief period of time. In the more recent and sophisticated localisation models provided by quantum state diffusion theory this process of localisation corresponds to a version of Brownian drift on the Bloch sphere that represents the quantum state of the system (see Percival, 1998, for a complete overview).

On the GRW collapse theory an isolated, closed, quantum system will undergo a spontaneous transition that localises it within a region of space of dimension $d = 10^{-5}$ cm *very infrequently*, more precisely with a frequency $f = 10^{-16}\,\mathrm{s}^{-1}$. In other words, such a system gets spontaneously localised every 100 million years on average, and for most practical purposes we can assume its evolution to be indefinitely quantum-mechanical. Yet, when such a system is part of much larger macroscopic composite, its spontaneous transition will trigger the collapse of the whole composite, previously entangled in a massive superposition state. Since macroscopic objects are composed of the order of 10^{23} such particles, it turns out that such triggering processes will take place on average every 10^{-7} s. This is shorter that the time required to complete a measurement interaction with

[20] Ghirardi, Rimini, & Weber (1986) is a landmark. Ghirardi (2002) provides a good overview.

the composite, which explains why we never experience macroscopic objects in superpositions, and always observe them highly localised in space.

The GRW theory models such spontaneous collapse processes as "hits", with the relevant frequency, of the quantum state by a Gaussian function appropriately normalised: $G(q_i, x) = K\mathrm{e}^{-(1/2d^2)(q_i - x^2)}$, where d represents the localisation accuracy, and q_i represents the position of the i particle. The wavefunction of an n-particle system, denoted as $F(q_1, q_2, \ldots, q_n)$, undergoes a transition with each hit that results in the new wavefunction: $L_i(q_1, q_2, \ldots, q_n; x) = F(q_1, q_2, \ldots, q_n)G(q_i, x)$. For my purposes in this essay it is sufficient to note that such a localisation procedure is at the very least compatible with the assumption that each quantum particle has an irreducible disposition to localise in an area given by d with frequency f. But moreover, on the GRW theory, the particle has a certain probability to localise in each area d in its position space given by the appropriate quantum probability as calculated by the standard application of the Born rule to its wavefunction. That is, the probability that it localises on a particular region x of space is given by $|P_x \Psi|^2$ in accordance with Born's probabilistic postulate, where P_x is the projector upon that region. In other words, the dispositions that according to GRW each particle has to spontaneously reduce upon a region x of area d are propensities, in the sense that I elaborated in Section 6. (For a similar view, see Frigg & Hoefer, 2007.)

It is clear on the other hand that the propensities that these GRW dispositions are not exactly selective-propensities, since the GRW transitions are spontaneous and not the result of selective interactions with measurement devices. This is an obvious difference with the selective-propensities account, which presupposes that a closed quantum system always evolves in accordance with the Schrödinger equation. Nonetheless, it is remarkable that the spontaneous localisation propensities that systems are endowed with on this reading of GRW are in all other respects like selective propensities.[21]

7.2. Bohmian mechanics

As is well known, Bohmian mechanics is an alternative hidden variable theory that is provably empirically equivalent to quantum mechanics, while preserving many ontological features of a classical theory. Most notably Bohmian mechanics conceives of quantum particles as point-particles, always endowed with a particular location in space and time, and it ascribes to them fully continuous classical trajectories. A minimal version of the theory can best be summarised in four distinct postulates:

(i) The state description of an n-particle system is given by (Ψ, Q), where $\Psi(q, t)$ is the quantum state with $q = (q_1, q_2, \ldots, q_n) \in \Re^{3N}$ and $Q = (Q_1, Q_2, \ldots, Q_n)$, where $Q_k \in \Re^3$ is the actual position of the kth particle.

(ii) The quantum state Ψ evolves according to the Schrödinger equation:

$$i\hbar \frac{\mathrm{d}|\Psi\rangle}{\mathrm{d}t} = \hat{H}|\Psi\rangle,$$

[21] The account of propensity required to make sense of the more sophisticated localisation processes of QSD and Pearle's continuous localisation theory are even closer to selective-propensities, since on those theories localisation is supposed to emerge in the interaction of the systems with the environment, if not a measurement device.

where H is the Hamiltonian:

$$H = -\sum_{k=1}^{N} \frac{\hbar^2}{2m_k} \nabla_k^2 + V(q),$$

with

$$\nabla_k^2 = \partial^2/\partial q_k^2,$$

and where $V(q)$ is the classical potential for the system and m_k is the mass of the kth particle.

(iii) The velocity of the N-particle system is defined as

$$v^{\psi}(Q) \equiv \frac{\mathrm{d}Q}{\mathrm{d}t} \quad \text{where } v^{\psi}(Q) = (v_1^{\psi}, v_2^{\psi}, \ldots, v_N^{\psi})$$

is a velocity field on the configuration space $\Re^{3N}$ that evolves as a function of Q according to

$$v_k^{\psi} = \frac{\hbar}{m_k} \mathrm{Im} \frac{\nabla_k \Psi}{\Psi} = \frac{\mathrm{d}Q_k}{\mathrm{d}t} \quad \text{where } \nabla_k = \partial/\partial q_k.$$

(iv) The 'quantum equilibrium' configuration probability distribution for an ensemble of systems each having quantum state Ψ is given by $\rho = |\Psi|^2$.

Postulates (i) and (ii) are the extension of quantum mechanics to an n-particle system. Postulate (iii) is unique to Bohmian mechanics: it guarantees that each particle has a classical continuous trajectory is physical 3-d space, and an n-particle system has a corresponding velocity field in the n-dimensional configuration space. Finally, the quantum equilibrium postulate (iv) guarantees the empirical equivalence between Bohmian and quantum mechanics. The postulates make it very clear that Bohmian mechanics, even in this minimal version, is not merely an interpretation of quantum mechanics—it is rather a distinct theory in its own right. It does not just provide an interpretation of quantum mechanics, but advances a whole theoretical machinery of its own, while making sure to account for all the successful predictive content of quantum mechanics.

Since Bohmian mechanics is a theory in its own right, it makes sense that it should have multiple interpretations, just as quantum mechanics has a number of competing interpretations itself. Here I will mention just two, rather extreme versions of the so-called guidance and causal views. There are a number of further views that lie somewhere in between these two in terms of their ontological commitment—each of these views is underdetermined by Bohmian mechanics itself.[22] My aim in this section is just to show that propensities are *compatible* with Bohmian mechanics; for this purpose it is enough to show that they are compatible with one interpretation of Bohmian mechanics.

A minimal formal interpretation of Bohmian mechanics (the *DGZ minimal guidance* view) has been advanced by Dürr, Goldstein, and Zanghi (1992). According to these authors, postulates (i)–(iv) characterise the theory entirely; no other postulates are needed.

[22] Belousek (2003) is a good description and review of many of them, including the DGZ version of the guidance view, and Holland's version of the causal view that I discuss in the text; but also others such as David Albert's radically dualistic guidance view, Antony Valentini's pilot wave guidance view, etc.

On this interpretation Bohmian mechanics is a first-order theory, formulated entirely in kinematical terms: no dynamic concepts are required. In particular the DGZ interpretation rejects the need for the ontology of quantum sub-fields, or quantum potentials that is often thought to characterise Bohmian mechanics: all that is needed over and above quantum mechanics is the guidance equation as described in postulate (iii). This interpretation is an equivalent of the bare theory for Everett relative states, since it sticks to the conception of the phenomena in accordance to the theory, and refrains from making any additional suppositions regarding the causal or explanatory structure that might underpin and give rise to such phenomena. Hence the application of propensities to this interpretation of Bohmian mechanics is not likely, but only because no causal or explanatory concept whatever is demanded. It is worth noting that the interpretation has been contested precisely on account of its minimalism; for instance by Belousek and Holland, who claim that second-order concepts such as forces are required if the theory is to retain its claim to greater explanatory power (Belousek, 2003, p. 140; Holland, 1993).

The family of interpretations of Bohmian mechanics that falls under the "causal view" rubric adopt an additional postulate regarding the quantum potential; this postulate describes the second-order dynamical concepts that according to this view are indispensable for a proper causal and explanatory physical theory (Bohm, 1952, pp. 170; Bohm & Hiley, 1993, pp. 29–30):

(v) The quantum state $\Psi = R \cdot e^{iS/h}$ gives rise to a quantum potential:

$$U = -\frac{\hbar^2}{2m}\frac{\nabla^2 R}{R},$$

so that the total force (classical plus quantum) influencing the trajectory of a particle is (the particle's equation of motion): $\vec{F} = -\nabla(V + U) = \mathrm{d}p/\mathrm{d}t$.

This postulate is introduced in analogy with classical mechanics, but it contains an additional element in the form of the quantum potential U, a dynamical second-order entity, responsible for the quantum force $-\nabla U$ that appears in the particle's equation of motion. These terms, the quantum potential U and the related quantum force field $-\nabla U$ are essential to explain particle trajectories, on any of the views often referred to as "causal"—but they demand an interpretation of their own, which differs on each of the causal views.

Holland's is perhaps the best known "causal view" today—it is also possibly the closest to Bohm's original interpretation and remains most committed ontologically. For an n-particle system, Holland assumes that each of the particles and their properties in physical 3-d space are real—which guidance views accept—but in addition he postulates the existence of the wavefunction and its associated quantum potential and force field in n-dimensional configuration space (Holland, 1993, pp. 75–78). This forces him to give an account of the causal interaction whereby the potential and force fields in configuration space affect the trajectories of the particles in 3-d space; an account that turns out to be enormously complicated and fraught with conceptual difficulties. (For an account of some of these difficulties, see Belousek, 2003, pp. 155–161.)

In response Belousek (2003, p. 162) has proposed that the quantum potential and force field are "real"—thus justifying postulate (v)—but only if interpreted as a catalogue of all possible interactions between the n-particles in physical space, not as distinct entities in an abstract configuration space.[23] My suggestion would be to reinterpret the quantum potential and force field along similar lines—except the modalities described by the quantum wavefunction in configuration space now describe a full catalogue of the propensities of the system. In the case of the two particle system formed by a quantum object subject to an interaction with a measuring device, this boils down to writing down each and every possible interaction between the measurement device and the propensities $\{O_1, O_2, \ldots, O_n\}$ of the quantum system described by its corresponding standard representatives $\{W(O_1), W(O_2), \ldots, W(O_n)\}$. There is a sense in which the quantum potential and the force field are "real" on this view too—since propensities are real properties of quantum systems—but the existence of a distinct space (configuration space) over and above physical 3-d space would not be required, thus avoiding the need to describe the causal interaction between these two spaces.

Interesting complications will arise in the case of *n-particle* systems subject to measurements. In these cases the trajectories of each of the particles (the only observable consequences of the theory according to Bohm) would be the result of not just the selective-propensities of each particle, but also the selective propensities of all the other particles as described through the quantum potential and the resulting force field would be the result of all the selective-propensities and their mutual interactions. Hence on this view the well-known non-locality of the quantum potential in Bohm's theory becomes a non-locality in the instantiation of propensities.

Thus the application of propensities to Bohmian mechanics would require the acceptance of postulate (v) as part of the core of the theory—in line with "causal" interpretations of Bohm's theory—but would then go on to interpret this postulate as a description of the highly non-local nature of each of the particles' selective-propensities, and their effect on particles' trajectories through the force field. Thus the propensity interpretation of Bohmian mechanics has all the advantages associated to the "causal" views of Bohmian mechanics, in particular its superior explanatory power in comparison with "guidance" views; but it purchases these advantages at a lesser ontological cost than most "causal" views—since it refrains from postulating the existence of a complex *n-particle* system in an equally real *n-configuration* space. Bohmian mechanics seems most fertile ground for the application of propensity views.

8. Conclusions

In the first four sections a number of conclusive objections were raised against previous attempts to employ dispositional properties in order to understand quantum mechanics (QM). So far, the history of dispositional accounts of QM may be considered a failure. But in Section 5, I presented the elements of a new account of QM in terms of selective-propensities that overcomes those difficulties. Section 6 explores some properties of selective-propensities, and provides the kernel of a philosophical defence. Section 7 sketches out ways in which similar dispositional properties can be read into two prominent and established competitors to orthodox QM: the GRW collapse theory, and Bohmian mechanics. There is no doubt that more detailed work is needed to provide a fully comprehensive treatment of the diverse interpretations and versions of QM in terms of

[23]The view is in some ways similar to Valentini's version of the pilot wave theory—see Valentini (1996) and Cushing, Fine, & Goldstein (1996).

dispositions. My hope is to have made a case that propensities afford an intriguing and progressive research programme in the philosophy of quantum physics that demands yet more philosophical work and attention.

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