Quantum Properties as Potentialities in Bohm's 1951 Book *Quantum Theory*[1]

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1. Introduction

A hundred years has soon passed since Werner Heisenberg in 1925 formulated matrix mechanics, the first complete formulation of quantum mechanics. This was followed by Erwin Schrödinger who in 1926 developed a mathematically equivalent wave mechanics which describes quantum systems using wave functions that evolve according to the Schrödinger equation. However, regardless of extensive discussions about the interpretation of quantum theory over the years that have passed, there is still no consensus among philosophers of physics what (if anything) quantum theory is telling us about the fundamental nature of physical reality. In other words, the metaphysical significance of quantum theory is unclear.

One factor (but not the only factor) here is that the philosophical climate in the 1920s when the first interpretations of quantum theory were developed was anti-metaphysical due to the influence of logical empiricism. Thus Niels Bohr said that the wave function should not be seen as a description of quantum objects, but rather as a part of a mathematical algorithm with the help of which we can predict the probabilities for the results of measurements that we observe in the classically describable parts of our measuring apparatus (i.e. as indicated by a macroscopic "pointer"). Because of Heisenberg's uncertainty principle we cannot observe quantum objects moving (we cannot measure their position and momentum accurately simultaneously), and Bohr thought (in the spirit of the verificationist theory of meaning of the positivists) that it is meaningless to talk

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about momentum when measuring position and vice versa. More generally Bohr thought that it is meaningless to try to provide a model or description of individual quantum objects. Many other physicists who adopted Bohr's "Copenhagen interpretation" had a similar anti-metaphysical attitude toward attempts to provide realist models of quantum objects. There were, however, significant differences between physicists often classified as supporters of what was known as the "usual", "standard", "text-book" interpretation or the Copenhagen view (see e.g. Howard 2004; see also Bohm and Hiley 1993, ch 2).

2. Bohm's metaphysics in his 1951 text-book *Quantum Theory*

One physicist who initially accepted the usual interpretation, but also had a desire to provide a more physical description of quantum reality was David Bohm. He is of course well known for proposing in 1952 a first consistent alternative interpretation of quantum theory in terms of non-local hidden variables (he independently re-discovered and completed the pilot wave theory de Broglie had presented in 1927; see Bohm 1952, Bohm and Hiley 1993). But it is less known that already in his 1951 text-book *Quantum theory*, when he was still working in the framework of the usual interpretation, Bohm was seeking a physical interpretation and tried to express quantum theory in terms of qualitative and imaginative concepts, in contrast to the very mathematical form in which quantum theory was originally developed. Here he clearly went beyond the anti-metaphysical, empiricist approach advocated by many in the Copenhagen camp.

In this short article we want to focus on one aspect of Bohm's 1951 interpretation, namely the way he thinks about the intrinsic nature of quantum objects, and the way he understands the quantum properties of matter. Let us first consider the issue of intrinsic nature. In classical physics it is customary to think that something has either a particle or a wave nature. Thus Newton thought that light consists of particles, while Young's interference experiments in 1801 established that light has a wave nature. Our ideas about the nature of light changed, but all along it was assumed that light had *some* intrinsic nature. According to Bohm quantum theory changed this radically. We have to give up the assumption that a quantum object such as an electron has an intrinsic nature as a particle or as a wave. Instead, quantum objects "…can act either like waves or like particles, depending on how they are treated by the surrounding environment" (1951: iii).

How should we then understand quantum properties (such as wave-like or particle-like properties) if they are not inherent properties? Bohm suggests that we ought to consider these properties as "… incompletely defined potentialities, the development of which depends on the systems with which the object interacts, as well as on the object itself" (1951:132). "Incompletely defined" should here be read in an ontological sense. Bohm acknowledges that the wave function is the most complete possible description of the electron that can be obtained by referring to variables belonging to the electron alone. But he emphasises that this description is incapable of defining the general form (wave or particle) in which the electron will manifest itself. So rather than the wave function describing definite pre-existing forms (e.g. particle or wave) that are revealed in an experiment, it only describes potentialities. These potentialities are actualized (i.e. become definite) only via interaction with a suitable measuring apparatus. (See Bohm 1951: 133).

These potentialities are also *opposing* in the sense that actualizing a given potentiality (such as wave-like behaviour) takes place at the expense of another potentiality (we cannot actualize particle-like behaviour in a situation in which wave-like behaviour is actualized) (1951: 138).[3]

Such postulation of potentialities to quantum ontology is a metaphysical move, and very different from the way in which Niels Bohr, for example, would characterise quantum reality (indeed, as we pointed out above, Bohr thought it meaningless to talk about the nature of quantum reality beyond what can be observed). Let us next see in more detail why Bohm characterises quantum properties as potentialities, and also explore further why he says they are incompletely defined.

He asks us to consider an electron with a broad wave-like packet, of definite momentum and, therefore, of a definite wavelength. (Remember the de Broglie relation $p = h/\lambda$ which implies that wave-length needs to be definite for momentum to be definite; here p is momentum, h is Planck's constant and λ is wave-length.) Bohm notes that such an electron is capable of demonstrating its wave-like properties when it interacts with a suitable measuring apparatus, such as a metal

[3] A referee was wondering whether by *opposing* Bohm just means something like that when you cast a die and the result is 2 then, at that instant, the probability of the result being 4 becomes zero. The point in quantum mechanics is that in the experimental context in which you actualised "2" (position) you could not have (even in principle) actualised "4" (momentum), whereas with the dice both actualisations are in principle possible in the same situation. So this analogy does not fully capture the quantum situation.

crystal. (The crystal functions in the same way as the slits in the familiar two-slit experiment, and we get wave interference effects if the wave packet passes through it.) But, he continues, the same electron is potentially capable of developing into something more like a particle when it interacts with a position-measuring device. When this happens its wave-like aspects become correspondingly less important. And we can keep on doing this, using again an apparatus that enables the electron to demonstrate wave-properties, and then using again a position-measuring device, and so on.

The bottom line is that the electron is capable of undergoing *continual transformation* from wavelike to particle-like aspect, and vice versa. It is the kind of apparatus with which the electron interacts which determines which of these potential aspects prevails. Importantly, Bohm notes that this also applies in situations outside experiments – for example with crystals at the bottom of the sea. While presentations of the usual interpretation of quantum theory usually talked about "observables" (as opposed to "beables"), and emphasized the need for a classically describable measuring apparatus, presupposing a human observer, Bohm sees the actualization of quantum potentialities as something that can take place in nature, independently of measuring apparatuses or human observers.

The quantum properties differ from the properties of classical physics not only because they are potentialities, but also because of the special role that probability has at the quantum level: "…these potentialities refer to developments, the precise outcome of which is not related completely deterministically to the state of the electron before it interacts with the apparatus" (1951:132). To illustrate this Bohm describes a position measurement. We start again with a broad wave-like packet and let it interact with a position-measuring device. After the interaction the wave function is broken up into independent packets. But, he says, the electron is found in only one of these packets. This means that from the wave function we can calculate only the probability that a given packet is the correct one. This, of course, is the familiar probabilistic aspect of quantum mechanics.

Bohm now makes a very interesting observation. He points out that the "…interpretation of the properties of the electron as incompletely defined potentialities finds its mathematical reflection in the fact that *the wave function does not completely determine its own interpretation*" (1951:133, italics added).

Let us assume that we are in a situation where the electron has not yet interacted with a measuring apparatus. In this situation the wave function defines two important kinds of probability, namely the probability of a given position and the probability of a given momentum. Now, Bohm points out that "…*the wave function by itself does not tell us which of these two mutually incompatible probability functions is the appropriate one*" (1951: 133, italics added). This question can be answered only when we design the experimental arrangement and in this way decide whether the electron interacts with a position measuring device or with a momentum measuring device.

Here we can see the special role that the experimenter has in quantum mechanics, as opposed to classical physics. In the latter we are used to thinking of the ontology of the physical world as actualized particles and fields in space, and our task as experimenters is to reveal the pre-existing values of the various variables in which we are interested. In quantum mechanics, in the way Bohm sets it up in his 1951 book, quantum ontology consists of a realm of incompletely defined and opposing potentialities, which require interaction with an environment to actualize them. And which potentiality of a single quantum object is actualized depends on the nature of the environment (e.g. whether it is a position or a momentum measuring device). In quantum experiments it is the experimenter who decides what to measure (e.g. position or momentum), and in this sense the experimenter plays a role in deciding which potentiality will be probabilistically actualized. This is very different from classical physics, where the experimenter is trying to reveal pre-existing values (see also Stapp 2007). Of course, one may ask here whether the choice of the quantum experimenter is "free", or whether it is determined by the laws of physics. And if the latter, which laws – classical, quantum, or some laws that have not yet been discovered?

3. An Ontology of Incomplete and Opposing Potentialities

Bohm aims to give a metaphysically robust interpretation of quantum mechanics which says something about the physical nature of quantum objects. Given this aim, one potentially interesting and instructive line of inquiry is to examine the extent to which Bohm's account might (or might not) comport with available general ontological frameworks. Whilst of course not decisive, should it be possible to identify a general ontological framework that fits well with Bohm's 1951 interpretation, it is reasonable to see this as a point in favour of *both* the interpretation of quantum mechanics under discussion and the relevant general ontological framework. Note also that because Bohm's 1951 interpretation is situated within the framework of the usual interpretation of quantum theory, the metaphysical implications are likely to extend beyond Bohm's specific ideas in the 1951 book and may apply to quantum theory in general. Overall, we envisage a metaphysics of science-based approach in which traditional metaphysical theorising and the natural sciences should be seen as mutually supporting and in dialogue with one another (see for instance Guay and Pradeau 2020).

Bohm's account is centred on four ontological claims about the features of quantum objects: first, that they are *potentialities*, in the sense that they exist without fully actualising or manifesting their whole nature; second, that the potentialities are *incompletely defined*, in the sense that the context in which they are situated is always a crucial and ineliminable factor on how they do in fact actualise or manifest in any specific, concrete instance, third, that the actualization of the potentialities is typically probabilistic; and fourth, that the potentialities can be to some extent *opposing*, in the sense that the actualisation or manifestation of a certain variable precisely can render impossible the actualisation or manifestation of a certain "complementary" variable, and vice versa (as discussed above in the case of position and momentum). In the rest of this section, we'll examine an ontological framework based around a particular conception of *powers* or *dispositions*—real potentialities—defended by, amongst others, Charlie Martin (2008), John Heil (2003) and Rögnvaldur Ingthorsson (2020), which we'll argue seems to fit quite well with Bohm's account of quantum potentialities.

We do not claim, however, that this is the *only* available framework, although we will note briefly that certain neo-Humean approaches (arguably the dominant general ontological framework in recent metaphysics) seem to struggle to accommodate something like Bohm's ontological proposals (with broadly neo-Aristotelian approaches looking more promising—we are, of course, not the only ones to point out the apparent affinity between Aristotelian frameworks and quantum potentialities: Heisenberg noted the connection (e.g. 1974, pp.16-17), see also Riezler (1940)). Why should neo-Humean approaches struggle? Briefly, the guiding picture of nature in the neo-Humean framework is what is often referred to as the 'Humean mosaic', a distribution of point-like purely intrinsic qualities over a four-dimensional spatio-temporal manifold. Amongst the elements of the mosaic, there are no necessary connections. Such a picture, at least *prima facie*, does not sit well either with the *incompleteness* or the *opposing*-ness of Bohm's quantum potentialities, as (i) *incompleteness* implies that various distinct elements (the quantum object plus various elements of the environment) are necessary for any given concrete actualisation and (ii) if the actualisation or manifestation of a certain kind of feature (e.g. position) of a quantum object precisely makes it impossible that some other feature (e.g. momentum) actualises or manifests, as the *opposing* nature of quantum potentialities requires, then again this involves the kind of necessity that a neo-Humean system typically abhors. We'll not dwell further on this point here, but move on to explore a more immediately promising approach.

Unlike with neo-Humeanism, neo-Aristotelian systems of various kinds embrace natural necessity. Neo-Aristotelian metaphysics is not a monolith, and there are various quite distinct guiding pictures of nature endorsed by different thinkers working within this broad framework—for instance, essence-centred accounts; hylomorphic accounts and powers-centred approaches (and these various elements can be combined, they are not mutually exclusive). Our focus will be powers-centred approaches, which seems a natural starting point given the centrality of the concept of potentialities in Bohm's 1951 theory.

Powers are features or properties which are essentially directed *to* something or other. That is, their nature involves being directed towards some manifestation or set of manifestations; and they bring about these manifestations in suitable circumstances (or, if some powers are stochastic—which may well be the case at the quantum level—will assign the same objective probabilities to their manifestations—henceforth we will omit qualifications of this sort, as it should usually be clear how the relevant claims can be modified to accommodate stochastic powers). As such, powers and potentialities go hand-in-hand—conceiving of properties as powers involves conceiving of them as having the potential to manifest or actualise something further. Canonical classical examples include fragility, which could be roughly characterised as 'the power to break when struck', or solubility, 'the power to dissolve when in contact with a suitable solvent' (these are used here merely as illustrations of the general idea—in the final accounting it may turn out that fragility or solubility are to be reduced to some more basic features). It is often suggested that we can roughly capture these features using conditional statements of the form:

> **P:** x has the power to φ if it is the case that were x to be placed in suitable circumstances C, then x would φ

We don't offer **P** as an *analysis* of what it is to have a power, but conditional statements such as **P**, even though they fail to analyse what it is to have a power, express key features of powers mentioned above: their directedness and their sensitivity to circumstance.

Inspired by something like **P**, what could reasonably be regarded as the *orthodox view* of powers in the contemporary debate holds that powers are single-track—each power is directed towards just one manifestation—and that they operate according to the *stimulus-manifestation* model—a power will only give rise to a manifestation when it is galvanised into action by some trigger or stimulus (e.g. Bird 2007). Whenever a single-track power manifests, and in whatever circumstances it does so, the manner in which it manifests is the same. According to the 'stimulus-manifestation' model, a power will only give rise to a manifestation when it is galvanised into action by some trigger or stimulus. For instance, in the case of the *fragility* of a vase, the stimulus might be ‘being struck with a force greater than X’, or in the case of the *solubility* of a sample of salt, ‘being submerged in water’. Crucially, the manifestation is produced by the target power alone, although it will not be produced until the occurrence of the stimulus.

The orthodox view, however, does not seem particularly well suited as a general ontological framework for Bohm’s account of quantum potentialities. The reasons for this are two-fold. First, whilst context has some role to play regarding what is actualised on a given occasion (by providing, or failing to provide, the stimulus conditions that trigger the manifestation or actualisation of the power), Bohm’s notion of *incompleteness* seems to point towards a more reciprocal relationship between the quantum object and the environment, where it is mutual interaction that gives rise to a specific manifestation on a given occasion. Second, it is hard to see how or why powers understood on this model would exhibit *opposing*-ness—that is, it is hard to see why, if the nature of a power is exhausted by its directedness to a single manifestation combined with sensitivity to a specific stimulus, the actualisation of one sort of manifestation on an occasion would make impossible the actualisation of another sort. The claim here isn’t that the orthodox view is strictly inconsistent with the *opposing* nature of quantum potentialities, but rather that some addition to the framework would be needed in order to account for it.

An *alternative view* holds that powers are *multi-track*—a single power is directed towards a (possibly very wide and diverse) range of qualitatively distinct manifestations—and that they operate according to the *mutual manifestation* model—in order for some manifestation to occur, there must always be at least two powers working together, and there is no sense of priority such that one power (or some subset of the powers involved) could be considered the 'operative' or 'active' power(s), whilst the other(s) are merely a stimulus or trigger. Note that this is distinct from the view (often associated with Aristotle) that powers come in *active/passive* pairings, where the active power plays the determinative role, and the passive power is a mere liability to be subject to changes associated with the manifestation of the active power. This alternative view of powers has been defended by for instance Martin (2008), Heil (2003) and Ingthorsson (2021), although we will focus on Martin's presentation here as he is particularly explicit concerning features of the view that are important in the present discussion.

Martin's account (he uses the language of 'dispositions' rather than 'powers', but for the purposes of this discussion they can be treated as synonyms) emphasises three features which seem, *prima facie,* to fit well with the key features of Bohm's theory which were mentioned at the start of this section. First, Martin is clear that "[a] particular disposition exists or it does not. You could say of any *unmanifesting* disposition that it straight-out exists, even if it is not, at that time or at any other time, manifesting any manifestation" (2008, pp. 1-2). Thus, it is clear that Martin's powers are well-suited to be understood in terms of *potentialities* conceived as genuine, albeit, as we will see momentarily, incompletely defined features of their bearers (in the relevant case, of the quantum object). Second, the notion of reciprocity and mutuality are at the very core of Martin's understanding of the operation of powers:

> The reciprocities of these dispositionalities for their mutual manifestations are many, deep and complex. The important point is that for a specific mutual manifestation, any particular dispositional state is itself only one among many other dispositional states that together form reciprocal disposition partners for their particular mutual manifestation. (ibid. p.3)

And

> One must take the *reciprocity* of a reciprocal readiness *partnerings* as their *mutual* manifestings seriously and not ask for the action of a single readiness factor only because there is no such action. Instead, actions are the *reciprocal* partnerings of a web or net of readiness. (ibid. p.22)

This conception of powers fits quite naturally with Bohm's notion of *incompleteness*, as described above as requiring that various distinct elements (the quantum object plus various elements of the environment) are necessary for any given concrete actualisation. For on such an account one could never conceive of the underlying potentiality of a quantum object alone as being responsible for the actualisation or manifestation of a determinate feature on a specific occasion—the context (experimental or natural) will always play an equally important and ineliminable role. And this is precisely what Martin's account holds about the nature of powers in general, that they are reciprocal to the core: what it *is to be* a particular power is in large part given by reciprocal relatedness to other powers. And, as the quote below mentions, Martin takes the readinesses, directednesses and selectivities of a power to run to infinity, so there is no sense in which a power can be thought to be 'completely defined' in isolation (this is an ontological point, not just a point concerning whether we could specify such a definition in language).[4]

Finally, Martin is explicit that the multiply-directed nature of powers is not limited to a range of 'positive' manifestation types, but also involves exclusion or suppression of alternatives:

> A particular dispositional state with its particular set of disposition partners *for* a particular set of manifestations with *different* sets of disposition partners (that may be infinite) will *not* be for or may even be *prohibitive* against manifesting an infinite number of manifestations… Dispositionalities *must* outrun manifestations, for dispositionalities can be for *alternative* mutual manifestations whose alternative disposition partners mutually exclude the concurrence of those mutual manifestations. (ibid. pp.3-4)

Once more, we can see that a conception of powers along the lines suggested by Martin seems to fit rather neatly with the idea that some potentialities can be *opposing*, as Bohm's theory requires—it should be part of our basic understanding of powers that the relationships between them, the way in which they reciprocally and mutually manifest and their manifestations themselves are complex, sensitive to circumstance and can involve exclusion or selectivity *against* alternatives as

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[4] We are grateful to a referee for pushing us to be more explicit about how Martin's view fits with incompleteness and opposing-ness.

much as they involve directedness *towards* what it is they actualise on some given occasion (e.g. under some specific measurement conditions). Thus, Martin's understanding of powers as both directed towards some (reciprocal, mutual) manifestations and prohibitive of others is well placed to accommodate the Bohmian notion of opposing potentialities, for it allows quite naturally that the actualisation of one manifestation (e.g. the reciprocal and mutual manifestations involved in a momentum measurement, which involves both powers of the quantum object and the measuring apparatus) may also be *prohibitive* against some other manifestations (including those that would need to be actualised for a position measurement).

Although the above discussion has been rather brief, we hope to have shown that the central ontological commitment of Bohm's 1951 quantum theory—*incompletely defined, opposing potentialities*—can be situated within an independently motivated general ontological framework such as the account of powers defended by Martin and others. This may not be the only possible framework, but we have tried to show that there is a natural fit here, and have also given some reasons to think that various alternative views—such as neo-Humean approaches and the orthodox contemporary view of powers—will have a harder time accommodating Bohmian quantum potentialities.

4. Does this really work?

Let us now go back to consider Bohm's account of quantum potentialities further. While the approach may sound *prima facie* interesting and viable, it has some puzzling aspects. To see this, let us consider a statement which summarizes Bohm's 1951 quantum metaphysics: "We … interpret momentum and position (and thus wave and particle aspects) as incompletely defined potentialities latent in the electron and brought out more fully only by interaction with a suitable measuring apparatus." (1951: 133) But here it is tempting to ask: doesn't the measuring apparatus itself consist of quantum objects whose properties are also "incompletely defined potentialities"? And if so, how can then sets of "incompletely defined potentialities" actualize "incompletely defined potentialities"? Bohm does not address this question explicitly in his book, but the final short chapter of his book, "Ch 23 Relationship between quantum and classical concepts" (pp. 624-628) provides a discussion with which we can evaluate how he might have replied.

Our common intuitions about the nature of the micro and the macro and their relation might well suggest that we can derive classical concepts as limiting cases of quantum concepts. After all, isn't it obvious that macroscopic, classical objects consist of microscopic, quantum objects? And isn't it customary to think that quantum theory is more fundamental, so that it could be the basis from which classical theory and classical concepts could be derived as a special limiting case? It is one of the fascinating features of the usual, text-book interpretation quantum theory that this is not at all obviously the case. Let us examine how this can be seen in Bohm's 1951 quantum ontology.

As we have seen, according to Bohm quantum properties are incompletely defined potentialities which can be actualized only in interaction with a classically describable system (a measuring apparatus is a special case – the system could be a naturally occurring crystal at the bottom of the sea).

The wave function can be used to calculate the probability that when a system interacts with a suitable measuring apparatus, it will develop a definite value of the variable that is being measured. But the measuring apparatus itself cannot be understood as a purely quantum object (i.e. consisting only of incompletely defined potentialities), for its last stages are always classically describable. This means that after the measurement interaction we will find the macroscopic pointer of the measuring apparatus in a well-defined position, pointing to a definite result. And it is only at the classical level that definite results for an experiment can be obtained. Bohm continues:

> This means that without an appeal to a classical level, quantum theory would have no meaning. *We conclude then that quantum theory presupposes the classical level and the general correctness of classical concepts in describing this level; it does not deduce classical concepts as limiting cases of quantum concepts*. (1951: 625)

What about the correspondence principle? Does it not show that we can derive classical ontology as a limiting case of quantum ontology? No, says Bohm: "The correspondence principle is simply a consistency condition which requires that when the quantum theory plus its classical interpretation is carried to the limit of high quantum numbers, the simple classical theory will be obtained." (1951: 626).

Thus, the correspondence principle is not a direct derivation tool, but a condition ensuring consistency between quantum and classical theories.[5]

Bohm's discussion implies that quantum theory needs classical theory and its concepts as a foundational framework. This means that quantum theory is an incomplete description of physical reality: one cannot describe the large-scale behaviour of a system completely in terms of quantum concepts. Quantum concepts refer to incompletely defined potentialities, but in the classical level we find definite objects and events. These classical properties cannot be deduced from the quantum description in terms of the wave function, but they must nevertheless be consistent with the quantum description.

Does the world then divide into two independent realms, the classical level with classical properties and the quantum level with quantum properties? Of course not, for these levels depend on each other. We need well-defined classical events (e.g. a macroscopic pointer pointing at a specific value) to actualize quantum-mechanical potentialities. But reciprocally, we need a quantum theory of the component molecules of a macroscopic system to fully understand its large-scale behavior. Bohm summarizes the situation: "…large-scale and small-scale properties are both needed to describe complementary aspects of a more fundamental indivisible unit, namely, the system as a whole." (1951: 627)

All this suggests an interesting ontology for the world. The world can be divided to two interdependent levels (quantum and classical), which are very different in their nature and the tendencies that prevail in them. At the quantum level, Bohm says, there is a continual tendency for a system to cover the whole range of its potentialities, while at the classical level there is a continual tendency for things to become definite, i.e., for a specific potentiality to be realized at the expense of all other potentialities (1951: 627).

These two levels meet e.g. in the process of measurement, where the system settles down to a particular value of the measured variable and all other possibilities are discarded. This is connected to the idea of the collapse of the wave function. At the end of the process of measurement, there appears a definite result at the classical level (e.g. a macroscopic pointer is pointing to a specific value).

[5] In a well-known quote, to which physicists like to refer even today, Landau and Lifshitz (1974: 6) write: "…quantum mechanics occupies a very unusual place among physical theories: it contains classical mechanics as a limiting case, yet at the same time it requires this limiting case for its own formulation". If Bohm is correct the first part of Landau and Lifshitz's statement is strictly speaking incorrect, but they are pointing to an idea similar to the one Bohm emphasizes.

This is reflected back into the quantum level in the sense that a narrowing down of potentialities at the classical level is accompanied by a similar narrowing of potentialities at the quantum level. But at the quantum level such narrowing of potentialities for one variable (e.g. position) means that there will be a widening of the potentialities for the complementary variable (e.g. momentum). This widening influences our expectations about what will be observed at the classical level if we now make a momentum measurement. Bohm summarizes: "…in the continual interplay between the quantum potentialities and their classical realizations, the system is subject to an endless series of transformations." (1951: 627).

It is important to distinguish between the kind of 'levels' that we have suggested Bohm's ontology involves, and the conception of levels familiar from discussions concerning the autonomy of the special sciences. In this latter debate, those who resist the idea that the entities described in chemistry, biology and so on can be reduced, ontologically speaking, to micro-physical entities, often appeal to a hierarchy of compositional levels of being. The claim then developed is that the entities occupying 'higher' levels being dependent on but nevertheless somehow autonomous with respect to, their lower-level realisers. This is clearly not the same sort of relationship envisaged as obtaining between the quantum level of incompletely defined and opposing potentialities and the classical level of determinate, manifest being.

Rather, the quantum and classical levels are mutually dependent and presuppose each other. Again here, we might find a natural fit with Martin's general ontological framework, for he rejects both the notion of *pure* potentiality on the grounds that to move from potency to act, some determinate, manifest being is required (a world of pure potentiality would be a world of 'promissory notes' which are never made good on (2008, p.63)) and the notion of *pure* manifest or actualised being, on the grounds that being that is 'in pure act', that is, being that always manifests everything of which it is capable, would actually amount to non-being (at least in the case of concrete, material phenomena; Martin allows that abstracta such as numbers, should they exist, might be in pure act (ibid. p.54)). Thus, for Martin, whilst powers involve a kind of order of being with a rich structure that "outstrips" the manifest; nevertheless they presuppose some determinate, manifest being (as Bohm's level of quantum potentiality presupposes the classical level).

5. Discussion

One might wonder whether it is relevant, in 2024, to go back to Bohm's 1951 discussion of quantum properties as potentialities. We saw that Bohm himself there acknowledged that quantum theory presupposes the framework of classical physics, which cannot be seen as a satisfactory view for anyone who assumes that quantum theory is a complete description of the non-relativistic domain. However, as we pointed out in the introduction, the fact is that there is still no commonly accepted interpretation of quantum theory. A key part of this is that there is no commonly accepted view of the relation between the quantum level and the classical level. This is why a view such as the many worlds interpretation is taken by many to be a genuine option in the current debates. There is no commonly accepted account of how quantum theory gives rise to a single macroscopic world, and thus the idea of "many worlds" remains an option.

Given this, if one wants to avoid the assumption of many worlds, it is perhaps not such a bad option to accept that currently the quantum theory presupposes the classical level. This is to acknowledge that quantum theory is incomplete, and that something new is needed if we want to derive a single, unique classical world from the quantum level. Bohm's later 1952 "pilot wave" theory provides one way to do this; but while the theory has many attractive features, it is not universally accepted.

So perhaps Bohm's 1951 idea of quantum properties as potentialities is still a live option which deserves more attention. For one thing it suggests an interesting link between physics and metaphysics, as we have briefly indicated in this paper. There are also other authors who have recently moved to a similar direction. For example, in their paper "Taking Heisenberg's potentia seriously" Ruth Kastner, Stuart Kauffman and Michael Epperson suggest that "…quantum theory is best understood as requiring an ontological dualism of *res extensa* and *res potentia*, … understood as mutually implicative ontological extants that serve to explain the key conceptual challenges of quantum theory; in particular, nonlocality, entanglement, null measurements, and wave function collapse" (2018: 158). While they do not refer to Bohm's 1951 discussion but rather Heisenberg's 1955 and 1958 discussions of potentialities, they make similar suggestions as already Bohm did, while introducing new interesting insights.[6]

[6] For other discussions of the role of potentialities in quantum theory see e.g. Fleming 1992; Kožnjak 2020; for a discussion in the context of theology, see Korpela 2022. Kistler 2018 provides

We also suggest that seeing quantum properties as potentialities provides a middle way between on the one hand very counterintuitive "actualist" views (such as Many Worlds (Wallace 2012) or Wave Function Realism (Albert 1996, Ney 2021)) and on the other hand radically epistemic and subjectivist neo-Bohrian views such as QBism (Fuchs, Mermin and Schack 2014). The idea that potentialities are a fundamental aspect of the quantum world also fits nicely together with the suggestions that both quantum gravity and quantum nonlocality suggest the need to consider a non-spatio-temporal order, from which space-time emerges (see Ismael 2020, Bohm 1980, ch 7).

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