(Draft version.)

Dispositions and Quantum Mechanics

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Overview

My aim in this paper is to raise, and discuss, some interesting questions about the metaphysics of dispositions and the interpretation of quantum mechanics ('QM'), questions which have received little or no attention in the literature on the philosophy of QM,[1] or in the literature of general metaphysics. After a few brief preliminaries, I will lay out the interconnected set of questions I have in mind. I will then go on to provide at least a partial answer to one of them, namely, the question of whether employment of the notion of a dispositional property can help us in the interpretation of QM.[2] Part of my answer will focus on the Bohm theory, an interpretation of QM which has been attracting much attention of late. I will propose a sort of reinterpretation of the Bohm theory, one which relies heavily on the notion of a disposition; the resulting interpretation of QM has certain significant ontological advantages over the orthodox version of the Bohm theory. Consideration of a variant on the standard EPR-Bohm experiment, however, makes it clear that, from a metaphysical point of view, some of the

[1] Though see Thompson (1988).

[2] A longer version of this paper also contains discussion of two of the other questions I raise. See n. 17 and n. 26.

dispositions one has to invoke on this new Bohmian interpretation have a rather curious feature.

Dispositions, propensities, and capacities

One presupposition of my line of thought will be that there is a distinction to be drawn between two sorts of property, the dispositional and the categorical.[3] We have some grip on the intended distinction insofar as we know how it is supposed to apply to certain paradigm cases, such as solubility, fragility, and malleability on the one hand,[4] and triangularity, tallness, and flatness on the other.[5] Giving an explicit account of the distinction is, however, no easy matter. There is clearly an intimate link between dispositional properties and associated types of behaviour: being a fragile object is importantly related somehow to breaking in certain sets of circumstances, and being a malleable one is similarly related to deforming. The usual attempts to articulate a systematic account of the distinction between dispositional and categorical properties then rely on the idea that a tight connection to behaviour is the distinguishing feature of dispositions. Clearly, however, an account of the distinction needs to say more about the precise nature of this connection.

[3] The term 'categorical' has associations which I do not wish to invoke here; I mean it simply to be synonymous with 'non-dispositional.' I will persist in using it, nonetheless, for stylistic reasons.
[4] Of course, one major source of philosophical interest in dispositions has been the idea that some, or perhaps all mental properties are dispositional, but on the whole examples from this realm will be controversial.
[5] This is, of course, not to deny that there might be room for disagreement over certain cases. Inertial mass, for example, is sometimes taken to be a paradigmatically categorical property, but there are arguments which purport to show that it is a disposition. (For further discussion of this case, see Mackie (1973), pp. 148-53, Mellor (1974), pp. 114-15, and Prior (1985), pp. 63-66.) Redness notoriously provides another disputed case.

In this regard, it has often been claimed that dispositional ascriptions entail, and are entailed by, conditionals dealing in the circumstances and behaviours which are supposed to be intimately related to the disposition in question.[6] For example,

X is fragile

might be thought to entail, and to be entailed by,

If *X* were dropped, it would break,

or perhaps more cautiously,[7]

If *X* were dropped right now, and in the right way, it would break.[8]

There are at least two problems with trying to account for the distinction between dispositional and categorical properties in this way, however.[9] First, it is quite unclear how a general criterion of dispositionality is to be abstracted from consideration of such examples. Clearly it will not do to say that ϕ-ness is a disposition if and only if there is

[6] See, e.g., Prior (1985), ch. 1 and ch. 5, section 1. Mackie has a more complex view -- see his (1973), pp. 125-33.

[7] The first qualification is intended to allow for the fact that dispositions can be gained and lost; the second, for the fact that not all ways of dropping a fragile thing will result in its breaking. (See Goodman (1983), p. 39, for worries of the latter sort.) In the latter case, the hope is that 'in the right way' can ultimately be replaced by a purely qualitative description of a certain way of dropping things; the worry is obviously that if 'the right way' were understood to mean "a way which guarantees breaking," then everything would count as fragile.

[8] Mellor (1974, p. 113) and Mackie (1973, pp. 125-6) raise a common concern about whether the relevant conditional should be a counterfactual one in the usual sense. (Note, incidentally, that their grounds for concern do not arise if one adopts a Lewisian semantics for counterfactuals.)

[9] To employ the terms of the three-way distinction I elaborate immediately below: Clearly neither propensity ascriptions nor capacity ascriptions entail 'would' conditionals; instead, we would need to consider 'would, with probability *x*' and 'might' conditionals, respectively. The problems I am about to describe for the case of "sure-fire" dispositions and 'would' conditionals will carry over straightforwardly, however.

some subjunctive conditional which entails, and is entailed by '*X* is ϕ,' as this would presumably render all properties dispositional. A second try might involve placing emphasis on the idea that the relevant conditional must concern *X*'s *behaviour* in certain circumstances, but this is perhaps to rely on a distinction which is itself not entirely clear-cut, and in any case there is still room for debate about whether such a criterion would misclassify many paradigmatically categorical properties.[10] Second, it is at least arguable whether dispositional ascriptions really do stand in relations of mutual entailment to conditionals of the relevant sort -- whether, in the case of our example, '*X* is fragile' really does entail, and really is entailed by 'If *X* were dropped right now, and in the right way, it would break.' This issue has recently been discussed in detail by Martin (1994) and Lewis (1997), and I shall not rehearse their arguments here.

Overall, then, I find myself in the somewhat uncomfortable position of one who persists in employing a crucial distinction without having an explicit and systematic account of that distinction ready to hand. Uncomfortable as this position may be, however, it is hardly an unusual one to be in.[11]

More can be said about the relations between the notions of a disposition, a capacity, and a propensity. I take it that at least in standard philosophical usage, these notions are distinguished in something like the following way: If we say that *X* has a disposition to ϕ (burn, break, bend...), then we take it that there are types of circumstance in which *X* would definitely ϕ. If, on the other hand, we say that *X* has a propensity to ϕ, then this is not assumed; instead we take it only that there are types of circumstance in which there is a certain (objective?) probability that *X* would ϕ.[12] (In part this is to say that *X* might ϕ in such circumstances; that if it were placed in such circumstances repeatedly, it very likely would ϕ sooner or later; and that, in the long

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[10] See Mellor (1974), p. 115, and Prior (1985), pp. 59-62.
[11] Not everyone, of course, will find this thought consoling.
[12] Mellor, for example, seems to distinguish between talk of dispositions and talk of propensities in this way (1974, esp. pp. 120-1).

run, there would be some stable frequency with which it would ϕ.[13]) Finally, if we say that *X* has the capacity to ϕ, then we merely commit ourselves to the claim that there are circumstances in which *X* might ϕ, without necessarily taking it either that there are any circumstances in which it would definitely ϕ, or even that it would have any well-defined chance of ϕ-ing in any particular circumstances. The claim that *X* has a capacity to ϕ is thus, in this sense at least, the weakest of the three.[14]

These remarks are intended neither as claims about the precise definitions of the terms in question nor as stipulative edicts; I mean only to characterise some of the associations that these terms often have. Despite the title of this essay, my point in doing so is not to exile capacities and propensities -- not at all. Indeed, given the distinctions I have just delineated, the notion of a propensity seems in many ways the most appropriate to the task of understanding the quantum-mechanical wavefunction. Nonetheless, and perhaps somewhat perversely, I will hold to the term 'dispositions.' This is partly because I wish to avoid certain associations of the term 'propensities': in the context of a discussion of QM, it calls to mind a particular interpretive approach due to Karl Popper[15]; more generally, it reminds one of certain issues concerning the interpretation of probability theory, and, for the moment at least, we shall be attempting to leave those issues aside. Another reason for preferring the term 'disposition' is that one of my central aims here is to forge links between questions concerning the interpretation of QM and certain issues in metaphysics, issues which have typically been

[13] Note that I do not say that this talk of stable frequencies tells us what it *means* to say there is a certain probability that *X* would ϕ.

[14] On the other hand, capacity talk perhaps sounds more robustly causal in some contexts than talk of propensities or dispositions: ascribing a capacity for ϕ-ing to *X* is perhaps most fitting when ϕ-ing involves causing a change in others, rather than simply being the subject of a change. To put it another way, perhaps a property is more likely to count as a capacity insofar as possession of that property equips its possessor to be an agent, rather than a patient. On this way of dividing up the territory, then, toxicity is a capacity in a sense in which fragility, say, is not. (Intuitions of this sort are reflected in the way Nancy Cartwright regiments her terminology at certain points in *Nature's Capacities and their Measurement* (1989) -- see p. 226.) Nonetheless, we certainly can speak without impropriety of something's having the capacity to bend when it is flexible, and so for the sake of neutrality I will not suppose any implication of causal agency or its absence to be built into the notions of disposition, propensity, or capacity.

[15] For Popper's "propensity interpretation" of QM, see his (1957), pp. 68-70, the "Postscript: After Twenty Years" to his (1959), and his (1982), pp. 64-74.

discussed with respect to the strong, deterministic notion of a disposition outlined above. However, much of what has been said in regard to those standard metaphysical issues would seem to apply equally well in the case of propensities and of capacities. In consequence, I'll say 'dispositions,' but mean "dispositions or propensities," or even "dispositions or propensities or capacities."[16]

Some interesting questions

Each of the questions I wish to raise falls into one of two categories, corresponding to two general questions one might ask:

> Can we learn anything about the metaphysics of dispositions by examining the various interpretive issues which arise with regard to QM? (Or even just by examining QM?)

and, on the other hand:

> Can we learn anything about the interpretive options with regard to QM by thinking about the general metaphysics of dispositions?

I take it that the answer to either of these questions could, in principle, be 'yes.' That is, I take it that there is (or should be) a complex interplay between the philosophy of physics and general metaphysics in which each influences the development of the other. This assumption, however, is one that I will not attempt to defend here, except insofar as, by

[16] Such usage is not entirely without precedent: Mackie uses 'disposition' to cover both "sure-fire dispositions," as he calls them, and "probabilistic dispositions," by which he seems to mean propensities in the sense described above (1973, pp. 121-2).

tackling certain specific questions along the lines of the two general questions just stated, I manage to make it seem plausible that, in this region at least, there are links.[17]

So, on to the specific questions.

Question 1

> One might read quantum-mechanical state descriptions as, at least in part, ascribing a large number of dispositions to the systems they purport to describe. Does reading the state descriptions in this way help us with any of the interpretive problems of QM?

This is the question on which I will be focussing in the remaining sections of the paper. Exploring it will in part involve considering the roles dispositions play, or might play, in various specific interpretations of QM; in particular, we will consider the orthodox interpretation, so-called, certain of the modal interpretations, and the Bohm theory.

Question 2

> Does interpreting QM, or reading various interpretations of it partly in terms of dispositions show us anything about whether dispositions must or can have bases? Or about the relations of dispositions to their bases, if they have them?

In J. L. Mackie's characteristically restrained but pointed words, "[D]ispositions and powers are disturbingly reminiscent of faculties, dormitive virtues, and the like, and it is widely believed that there is something fundamentally wrong with concepts of this

[17] Doubts on this score are most likely, at least amongst philosophers, to take the form of doubts about whether the interpretation of QM can, or should, influence metaphysics. In this version of the paper, however, I offer answers only to question 1, which concerns one way in which metaphysics might influence the interpretation of QM. Nonetheless, in the longer version of the paper I also consider questions 2 and 3, and show how the interpretation of QM might push our metaphysics in a certain direction. See n. 26.

group, though few would be able to say exactly what is wrong with them" (1973, p.121). Driven partly by this suspicion of dispositions, many have claimed that such properties, when they are present, must have *bases*: that is, the possessor of the disposition must have other features in virtue of which it has the disposition, properties which are then said to "ground" the disposition. Accordingly, the basis is usually supposed to be categorical,[18] so that somehow the mystery attendant upon the disposition is dispelled -- a sort of metaphysical money-laundering operation.

Once this general idea has been introduced, a host of questions follows, none of which will come as a surprise to anyone who is familiar with much contemporary analytic metaphysics or philosophy of mind:[19] Do all dispositions have bases? Do they necessarily have them? Do they have them (when they do) necessarily? If dispositions do have bases, are they type-identical to them? Token-token identical? Do dispositions merely supervene on their bases? Should one perhaps be a functionalist about dispositions?[20]

Although there has been much disagreement over the answers to these questions, majority opinion has certainly been that the idea of dispositions without bases is an intrinsically problematic one -- if not downright incoherent, then at least pernicious and to be avoided.[21] Few, however, have been willing to advocate a ban on talk of dispositions, or to classify such talk as confused, unscientific, or meaningless, and so the tendency has been to offer what we might call "deflationary" accounts of one sort or another. Very often, such accounts try to make it plausible that in ascribing a

[18] Although see Armstrong (1973), ch. 2.II.
[19] As noted above (n. 4), interest in the general metaphysics of dispositions has been stimulated by the idea that some, or even all mental properties might be dispositions; it is thus no accident that the range of positions which have been taken on the relations of dispositions to their putative bases closely parallels the range of positions which have been taken on the relationship of the mental to the physical properties of persons in the last fifty years or so.
[20] Note that one can question the extent to which talk of "type-type" and "token-token" identities can be made coherent in this context. I discuss these issues in more detail in the longer version of this paper; Prior (1985) contains extended discussion of most of them.
[21] Mellor (1974) and Martin (1994, 1996) are notable exceptions.

dispositional property to an object we are really just making an indirect, partial, or disguised claim about the sorts of categorical property it possesses.[22]

On this score I find myself siding with the minority who maintain, on the contrary, that at least some dispositions are just as much first-class citizens of the world as the most respectable of categorical properties, that there are dispositional properties which are just as deserving of being numbered amongst the fundamental or basic features of things as, say, squareness (so that these dispositions are not in any sense reducible to any collection of categorical properties, or anything else), and that it is the fear and suspicion of dispositions which is in need of philosophical treatment, rather than our otherwise carefree tendency to think, talk, and theorise in terms of them.[23]

One more specific and provocative question along the lines of question 2 is thus:

Question 3

> Does reflection on QM give us good reason to admit irreducible dispositions into our ontology? Might it even force us to do so?

Note that a disposition counts as "irreducible" in the intended sense just in case it has no basis, categorical or otherwise; just in case, that is, objects which have the disposition need not have any other feature, or collection of features, in virtue of which they manage to have the disposition in question.[24]

The answer to at least the first part of this question might be 'yes' if, for example, the only way we can understand any of the feasible interpretations of QM is as (in part) ascribing irreducible dispositions to systems. This suggests a connection between this question and the first: the question of whether the notion of a disposition can help us to

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[22] On Ryle's account, on the other hand, it seems that (so-called) dispositional ascriptions should not be thought of as making claims in the ordinary sense at all. See Ryle (1949), pp. 123-25.
[23] Other members of this minority party are Alston (1978, p. 387, n. 12), Mellor (1974) and Thompson (1988).
[24] Reduction in the intended sense would thus not necessarily require anything as strong as identification with some other property or collection of properties.

interpret QM and the question of whether we can understand the various interpretations of QM at all without recourse to the notion of an irreducible disposition are not so far apart.

Two further comments: (i) Obviously interpretive reflection on QM can only have implications for our ontology if we take an appropriately realist attitude to the theory. That we can and should take such an attitude is another assumption which must remain in the background here. (ii) I would not want to suggest that no good or compelling reasons for allowing irreducible dispositions into our ontology can be found elsewhere;[25] be that as it may, however, it is surely of independent interest whether QM provides us with reasons of its own. In fact, I think that QM does give us good reason to deny that all dispositions have bases, because it gives us good reason for denying that the dispositions of a given physical individual supervene on its nondispositional properties.[26]

Question 4

> Does consideration of QM throw any light on questions about the respectability of appeal to dispositions in explanation?

Surely one of the most commonly occurring literary allusions to appear in present-day philosophical writing is a reference to *Le Malade imaginaire*, in which Molière lampoons the medical science of his day by having Argan, the hypochondriac, respectfully quote a

[25] Even this way of putting the matter has its misleading aspects. I suspect that irreducible dispositions are already quite firmly ensconced within our ontology, and that it is only by dint of considerable effort that we can reach the point of considering whether they might be extractable therefrom.

[26] I discuss the reasons QM provides for recognising irreducible dispositions in the unabridged version of this paper. (The issue quickly becomes a complex one, involving, for example, questions about the interpretation of the projection operator which projects onto the ray containing the state vector of a system in a pure state.) I supplement my argument there with a critique of functionalism about dispositions, which, I argue, is the most promising sort of deflationary account. (See Prior (1985), chs. 6 and 7, and Prior *et al*. (1982).) Ultimately, I also hope to include responses to arguments by Armstrong (1968, ch. 6, sec. VI) and Prior, Pargetter, and Jackson (1982) which purport to show that dispositions necessarily have bases. (Tooley (1972), Mackie (1973 pp. 130-32), and Mellor (1974, pp. 110-11) all criticise Armstrong's argument, but in my view none of them locates the problem perfectly.)

doctor's pronouncement that opium puts people to sleep because of its "*virtus dormitiva.*" Clearly Argan and the good doctor are deserving of ridicule; nonetheless, it does seem that ascriptions of dispositions, when used in the right way, can play a crucial role in perfectly good explanations. Perhaps, if QM can or should be thought of as making such ascriptions, we can learn something from it about exactly how, and when, dispositions can explain. (If, on the other hand, we should become convinced that dispositions are explanatorily impotent, then perhaps we will be forced away from certain interpretive approaches to QM, on pain of finding QM equally explanatorily powerless.[27] Clearly things could add up in various ways here.)

Question 5

> On a number of ways of interpreting QM in dispositional terms, the properties of a given quantum-mechanical system will be, on the face of it, overwhelmingly dispositional. Could the view that all properties are (in some sense) dispositional help us to swallow this idea?[28] Or, conversely, do problems for that general view translate into problems for this sort of attempted reading of QM?

I will say no more about this question here. Instead, let us round off this list of questions about dispositions with one further, related question about QM: What are the primary and secondary qualities in QM, insofar as the distinction can be made out in that theory, or at all? I mention this question because it is clearly related to issues about dispositions, and because I have encountered the claim that, although modern physical theory is very different from that of the seventeenth century, the primary and secondary qualities have remained constant. This seems less than obvious to me.

[27] Of course, such reasoning will have no hold on one who, perhaps quite cheerfully, already regards QM as devoid of explanatory power.

[28] See, for example, Popper (1957), p. 70, and Mackie (1973), pp. 148-53.

Thus far I have primarily been concerned to set an agenda. Let me now begin to take myself up on it. I will be focussing on the first of the questions posed in the preceding section, namely, the question of whether reading quantum-mechanical state descriptions as, at least in part, ascribing a large number of dispositions to the systems they purport to describe can help us with any of the interpretive problems of QM.[29] In particular, can reliance on the notion of a disposition help us to fill out the specific interpretations of QM which are supposed to provide solutions to its interpretive problems?

We begin with the "orthodox interpretation." Whilst it is not always clear just what the dictates of orthodoxy are (and whilst, in particular, it is not clear just how much Copenhagen they contain), one of the defining features of the orthodox interpretation is subscription to the eigenstate-eigenvalue rule:[30]

$$S \text{ has a definite value of } A \text{ in } |\Psi> \text{ iff } |\Psi> \text{ is an eigenvector of } \hat{A}. \qquad \text{(EV)}$$

Yet more needs to be said before we can take ourselves to have fleshed out an adequate set of rules for interpreting the assignment of a given state vector, $|\Psi>$, to a given system.[31] Suppose that two state vectors, $|\Psi>$ and $|\Phi>$, agree in not being eigenvectors

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[29] For a much earlier discussion which can be read as examining the advantages of dispositions in interpreting QM, see Margeneau (1954), who contrasts "latent" with "possessed" observables; and Heisenberg famously invoked Aristotle, and talk of "potentia," at one point (1958, p. 160). See also Jammer (1974), p. 205 and pp. 504-7.

[30] A fuller statement of the rule is as follows: S has value a_i of A in $|\Psi>$ iff $|\Psi>$ is an eigenvector of $\hat{A}$ with eigenvalue a_i. (I follow standard conventions in denoting physical magnitudes by capital letters, and the Hermitian operators which represent them by capital letters topped with circumflexes.) The version of the rule given in the text is entailed by this version, the extra content of which is not immediately relevant to our discussion.

[31] I will simplify the discussion in many places by considering only the ascriptions of pure states to systems. It is a straightforward matter to generalise the points I will make to the case of mixed states which are not to be given an ignorance interpretation. (Ignorance mixtures, of course, are to be interpreted by combining an ignorance interpretation of the mixture itself with the interpretation of pure states I am about to sketch.)

of $\hat{A}$, and so, by (EV), agree in not assigning a definite value to A, but differ in the respect that

$$\exists a_i \text{ s.t. } \quad |<a_i|\Psi>|^2 \neq |<a_i|\Phi>|^2.$$

(Assume that $\hat{A}$ is maximal, for simplicity's sake; generalization to the nonmaximal case introduces no substantive differences.) Then surely we want to say that $|\Psi>$ and $|\Phi>$ say different things about the systems whose states they are used to represent; more specifically, they surely have different things to say about the systems they represent in regard to the quantity A. (EV), however, cannot capture such a difference, and thus requires supplementation.

Suppose, then, that we begin to fill out the orthodox interpretation with talk of dispositions. We adopt the interpretive rule that when $|\Psi>$ is not a eigenvector of $\hat{A}$ (for some $\hat{A}$), then although, by (EV), S in $|\Psi>$ does not have a definite value of A,[32] it does have certain "A-related dispositions."[33] And we add that the dispositions in question are partially individuated as follows: Two state vectors, $|\Psi>$ and $|\Phi>$, agree in the A-related dispositions they ascribe to a system iff $\forall a_i \ |<a_i|\Psi>|^2 = |<a_i|\Phi>|^2$.

Apart from going some way towards remedying the lack inherent in relying on (EV) alone, one obvious way in which such a liberal sprinkling of dispositions seems to help us in interpreting quantum-mechanical state descriptions along orthodox lines is that it allows us (at least at first sight) to understand how such state descriptions might be *complete* as descriptions of the states of individual physical systems, and thus makes

[32] In my view, and *pace* Paul Teller (1979, 1983), this orthodox locution is little more than a euphemism for 'S has no value of A,' one which serves mainly to conceal the fact that on the orthodox interpretation we must routinely claim that various physical objects have no location, to take only the magnitude which provides the most startling illustration of the problem. (Indeed, strictly speaking, the standard eigenstate-eigenvalue rule forces us to say that no quantum-mechanical system ever has a location, as the position operator has no genuine eigenvectors.)
[33] I am deliberately being somewhat enigmatic about the precise nature of these dispositions for the moment; the reasons for this will emerge soon enough.

room for the possibility that QM might be a complete theory of the systems in its domain.[34] The picture is this: A system *S* in state $|\Psi>$ has

i) a mass, a charge, a total spin, an isospin, ... ,

ii) a definite value of any observable *A* such that

$$\exists\, a_i \text{ s.t.} \hat{A}|\Psi> \;=\; a_i\,|\Psi>,$$

and

iii) a certain set of dispositions for each *A* such that

$$\neg\, \exists\, a_i \text{ s.t.} \quad \hat{A}|\Psi> \;=\; a_i\,|\Psi>.$$

And that is all. It has no other properties.

Of course, this last claim will always be enormously false, if left without qualification. Any actual system in the domain of the theory will have innumerable properties which, though adequately describable in quantum-mechanical terms, are not captured by $|\Psi>$ because they are relational or historical properties (or both); some systems in the domain of the theory, furthermore, will also have properties outside the bailiwick of physics, such as aesthetic and mental properties. But of course, we never intended $|\Psi>$ to capture such properties. To say that a given interpretation of QM regards the state descriptions of the theory as complete is not to say that it takes those state descriptions to capture *all* the properties of the systems they represent, but only the properties within some circumscribed range. I will not endeavour here to elucidate the relevant sense of completeness by circumscribing that range. The point remains, nevertheless, that in the relevant and familiar sense of 'complete,' it is clear that the above interpretive prescription treats quantum-mechanical state descriptions as complete descriptions of the states of individual quantum-mechanical systems.

[34] Leaving aside, of course, separate concerns about Lorentz invariance and, ultimately, quantum gravity.

Note, incidentally, that by adding the interpretive postulates in question to the orthodox interpretation we are not suggesting that the system has *only* dispositional properties: apart from the dynamically invariant features listed under (i) (mass, charge, total spin, and so on), some or all of which may count as categorical, its state may also be an eigenstate of a categorical property, if any of the relevant physical magnitudes are to be counted as categorical.[35]

The problem, of course, is that the interpretive suggestion itself is quite incomplete. In particular, it so far says nothing about what sort of *A*-related dispositions a system is supposed to have when its state is not an eigenstate of *A*. Dispositions, by their very nature, have something to do with behaving in certain ways in certain sorts of situation.[36] So what sorts of behaviour, and what sorts of situation, might we invoke here? And how exactly is the behaviour (and thus the disposition) related to *A*?

The obvious suggestion is that when *S* is in the state represented by $|\Psi>$, and $|\Psi>$ is not an eigenvector of $\hat{A}$, *S* has a (chance) disposition to give rise to the outcome 'a_i' on ideal *A*-measurement, with probability $|<a_i|\Psi>|^2$, for each eigenvalue of *A*.[37] (One might also add that S has a chance disposition to acquire value a_i of the quantity *A* on ideal *A*-measurement for each a_i, with the corresponding probabilities. The resulting interpretation would make stronger claims, but would perhaps be more satisfying.) In response to this suggestion, it is tempting simply to cry "Measurement problem!" and turn away, but we will do well to pursue things a little further.

One aspect of the measurement problem is the one that Bell was especially sharp-tongued about: the notion of measurement, as it stands, is ill-suited to play a fundamental role in physical theory.[38] That, however, is a problem we might well be able

[35] Position seems like a good candidate, but then, as noted above (n. 32), there are no genuine eigenstates of position, strictly speaking.
[36] The vagueness inherent in this claim is deliberate: I mean to distance myself from a conditional analysis of dispositional ascriptions.
[37] Remember that we are taking $\hat{A}$ to be maximal.
[38] See Bell (1987), essays 5, 15, and 18.

to solve within the bounds of the dispositional approach. The task is just to specify, purely in terms of their physical characteristics, the types of interaction which we want to count as measurements for the purposes of elucidating the interpretation. And of course a lot of that kind of work has been done, and could be adapted here.[39] Solving the problem in this way would allow us to reject charges of vagueness and anthropomorphism attending the use of the term 'measurement.' In that regard, it seems natural to elaborate the dispositional approach to the orthodox interpretation by adding that, in assigning state $|\Psi>$ to *S*, we are also ascribing to it, via the Schrödinger equation, the disposition to interact in all sorts of other, non-measurement (and non-ideal measurement) ways with various sorts of system in various sorts of circumstances, circumstances which are specified by Hamiltonians and by state ascriptions for the other systems.

Nonetheless, there is, of course, more to the measurement problem. We have to explain how it is that measurement of *A* on *S* in $|\Psi>$ gives rise to an outcome at all. There are, however, familiar arguments for the claim that as long as we have the eigenstate-eigenvalue rule in place, the only way to get outcomes for measurements (where such outcomes are taken to be, or to presuppose the existence of, certain sorts of physical event) is to adopt a collapse theory, on which the Schrödinger equation does not hold universal sway over the evolution of the state vector.[40]

One option, then, is indeed to adopt a collapse theory.[41] Should we do so, there is perhaps room to maintain the dispositional extension of the orthodox interpretation when it comes to interpreting state descriptions.[42] Suppose, on the other hand, that for

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[39] See, for example, van Fraassen (1991), ch. 7, and works cited therein.
[40] This is a disputed claim; defending it here would take us too far out of our way, however, and we will shortly be considering no-collapse interpretations in any case.
[41] Perhaps in the form due to Ghirardi *et al*. (1986). (See Bell (1987), essay 22, and Albert (1992), pp. 92-111, for further discussion.)
[42] Note, however, that at this point we still have an interpretation which commits us to claiming that physical systems in the domain of the theory typically (or always, strictly speaking) fail to have a location. (See n. 32.)

various reasons we wish to avoid any sort of collapse theory.[43] This seems fairly clearly to require a renunciation of the eigenstate-eigenvalue rule,[44] and with it the hope of regarding quantum-mechanical state descriptions as complete; we must resort instead to some scheme for granting at least some observables definite values even when the ordinary quantum-mechanical state description fails to inform us about them (a scheme which we have carefully rigged, of course, in such a way that no Bell inequalities or Kochen-Specker-type contradictions are entailed). Does moving towards an interpretation of this type mean that dispositions no longer have a role to play? After all, we initially introduced dispositions as providing us with a way of supplementing the eigenstate-eigenvalue rule in the hope that we would be able to regard state descriptions as complete; if we choose to reject the rule, and relinquish the hope, what use will we have for dispositions?

I want to argue that there is plenty of useful work for dispositions to do even after we throw out the eigenstate-eigenvalue rule. For there is plenty to be done by way of filling out, and in some cases even reinterpreting the various interpretations of the theory which embrace the incompleteness of ordinary quantum-mechanical state descriptions. In the next section, I will illustrate this point by exploring certain problems with the Bohm theory. First, however, consider the way Bas van Fraassen characterises the two components required for a complete state description in his various modal interpretations (1991, p. 275):

> Value state: fully specified by stating which observables have values
>
> and what they are

[43] See Albert (1992), ch. 5.
[44] Leaving aside the Many Minds interpretation and certain approaches based on Everett's work, all of which proceed by throwing out the eigenstate-eigenvalue rule at another level, so to speak.

> Dynamical state: fully specified by stating how the system will
> develop if isolated, and how if acted upon in any definite, given fashion.

Van Fraassen adds: "...The concept of the dynamical state remains the primary one." The dynamical state is the one governed by the Schrödinger equation, the one used in the Born rule, and the one QM provides. The value state is the "hidden variable" that enables measurements to have outcomes, and it is constrained, although in general not fixed,[45] by the dynamical state.

By van Fraassen's own characterisation, then, it sounds rather as though specifying the dynamical state of a system (the "primary concept" on his approach) is a matter of ascribing a large number of dispositions to the system. Some of these dispositions will be deterministic (mainly the dispositions to acquire new dynamical states in various circumstances, all of which are deterministic in virtue of the absence of a collapse), and some will be probabilistic (including most, though not all, of the dispositions to acquire new value states in various circumstances). Van Fraassen himself might well want to gloss such talk of dispositions in terms provided by an account of modalities as living only in the models, and not in the world.[46] Given such a gloss, however, there is no obvious reason why he should not countenance such talk. Indeed, we might well ask how else we are to understand the concept of the dynamical state. And more realist proponents of one of van Fraassen's modal interpretations, or any of the more recent modal interpretations (such as those due to Dennis Dieks (1989) and

[45] Hence the moniker "modal interpretation": the state QM provides specifies the range of possibilities with regard to possessed values of observables. See van Fraassen (1972), p. 336. ff., esp. n. 46.
[46] See van Fraassen (1980), ch. 6, sec. 5.

Richard Healey (1989)), can feel free to regard the dynamical state as actually ascribing dispositions to electrons and the like.[47]

Dispositions and the Bohm theory

Let us now turn to see how we might make use of dispositional properties in understanding and elaborating the Bohm theory, an interpretation of QM which has been enjoying a renaissance of late. Although this renaissance is well-deserved in many ways, some strong claims have been made for the interpretation which are rather strikingly in tension with certain features of the theory on its usual reading. I will begin by describing the relevant difficulty, and then go on to propose a solution which involves reinterpreting the formal structure undergirding the Bohm theory. The interpretation of QM which results invokes irreducible dispositions at every turn. This, I would claim, is not a bad thing.[48] Some of the dispositions which the interpretation must posit, however, turn out to have a somewhat unsettling aspect of a quite different sort.

A good example of the kind of strong claims which have recently been made for the Bohm theory can be found in the chapter on Bohm's theory in David Albert's book, *Quantum Mechanics and Experience*:

> Here's what's so cool about this theory:
>
> This is the kind of theory where you can tell an absolutely low-brow story about the world, the kind of story (that is) that's about *the motions of material bodies*, the kind of story that contains nothing cryptic and nothing

[47] Healey is quite explicit about the role of propensities (or "probabilistic dispositions") in his interpretation; see his (1989), pp. 54-5 and *passim*. A word of caution, however: Healey uses the term 'dynamical state' for the component of his approach which is more closely analogous to van Fraassen's value state.
[48] I provide further argument in support of this claim in the longer version of this paper.

> metaphysically novel and nothing ambiguous and nothing inexplicit and nothing evasive and nothing unintelligible and nothing inexact and nothing subtle and in which no questions ever fail to make sense and in which no two physical properties of anything are ever "incompatible" with one another and in which the whole universe evolves *deterministically* and which recounts the unfolding of a perverse and gigantic conspiracy to make the world *appear* to be *quantum-mechanical*, (1992, p. 169, emphasis in original)

Note especially the phrase "nothing metaphysically novel."[49]

Now, however, consider Albert's description of the basic ontology of the Bohm theory:

> What the physical world consists of besides particles and besides force fields, on this theory, is (oddly) *wave functions* .... The *quantum-mechanical wave functions* are conceived of in this theory to be genuinely physical *things* ... as something quite distinct from the particles ... and the job of these wave functions in this theory is to sort of *push the particles around* .... (*op. cit*., p. 135, emphasis in original)

and, in a footnote to the passage just quoted:

> What [Bohm's] theory takes the wave function of a particle to be ... is a sort of genuinely physical *stuff*.

[49] Maudlin (1994, pp. 116-21), who clearly understands the Bohm theory in the same way as Albert, is considerably more restrained, but even he asks why Bohm's theory "has not simply displaced orthodox quantum theory," as he takes it to be largely "devoid of interpretational difficulties" (p. 119). (Maudlin mentions the problem I raise below only in passing, in his n. 20.)

> And the *physical properties* of such wave-functions-considered-as-stuff are ... their *amplitudes* at every point in space. (*ibid*., n.2, emphasis in original)

Bell understands the Bohm theory similarly:

> To the question "wave or particle?" [de Broglie and Bohm] answer "wave *and* particle." The wave Ψ(t, r) is that of wave mechanics -- but conceived, in the tradition of Maxwell and Einstein, as an objective field, not just a some "ghost wave" of information. (1987, p. 112, emphasis in original)

And, later on the same page, describing the two-slit experiment from a de Broglie-Bohm point of view, Bell writes:

> [T]he wave always goes through both slits, as is the nature of waves. (*ibid*.)

Thus far, perhaps, the tension between the protestations of metaphysical innocence and the interpretive picture we are being offered is not writ large. But now consider the following, from another paper by Bell:

> *No one can understand [Bohm's] theory until he is willing to think of **Ψ** as a real objective field rather than just a "probability amplitude." Even though it propagates not in 3-space but in 3N-space.* (1987, p.128, emphasis in original)

It is in this last sentence that all the trouble lies. '*N*' is the number of particles in the system; thus, for any system composed of more than a single particle, the associated "objective, real" quantum wave lives in a space of a larger dimensionality than physical space, and indeed, in a space of a *much* larger dimensionality for most systems.[50] And whenever the state vector for the system as a whole is mathematically nonseparable (i.e., whenever it cannot be written in the form[51] $|\phi_1>\otimes|\phi_2>\otimes...\otimes|\phi_N>$), which, especially on a no-collapse theory, is most of the time, we will not be able to regard it as simply a concise description of a number of distinct fields in 3-space; it will be definable *only* in higher-dimensional spaces. This thing, however, the "wave function," is supposed to be not only "real" and "objective," but *physical*. It is supposed to interact causally with all of its associated particles, guiding them on their carefully choreographed way through 3-space. In this respect at least, the Bohm theory can hardly be said to be metaphysically straightforward.

I do not wish to claim that it would be impossible to adjust ourselves to such a picture of the physical world. I simply want to suggest that all is not clear and unproblematic in the Bohm theory, so as to motivate a partial reinterpretation in dispositional terms .

The idea of the reinterpretation is quite simple: Hold onto Bohm's equations, and most of the picture that goes with them. In the one-particle case, for example, if the state of the system at *t* is represented by a certain mathematical object, $\Psi(x,y,z)$, then using

$$\Psi = R \exp\left[\frac{iS}{\hbar}\right],$$

we suppose that the particle has some definite location, is at (x',y',z') with ignorance probability

$$|R(x',y',z')|^2,$$

[50] A much larger dimensionality, what is more, than physical spacetime has even according to the various string theories.
[51] Or, more generally, as a tensor product of *N* density matrices.

and has then a velocity given by

$$\frac{d\underline{r}}{dt} = \frac{1}{m}\nabla S\Big|_{\underline{r}=\underline{r}'}$$

The "evolution" of Ψ, the mathematical object representing certain aspects of the state of the system, is governed by the Schrödinger equation (in the ordinary non-relativistic case); the motion of the particle is thus entirely deterministic.

So far everything is orthodox Bohm theory. But now let Ψ, instead of representing some physical entity which interacts with the particle, be understood to provide two sorts of information about the determinately located particle. First, it represents the particle as having a categorical property corresponding to every operator which represents a categorical quantity and of which it is an eigenfunction -- namely, the property of having the relevant eigenvalue of that quantity. (By "categorical quantity" I mean simply any determinable whose determinates are categorical properties.) Second, Ψ contains a certain sort of conditional information about the dispositions the determinately located particle has, in the following way: Given Ψ and the position of the particle, we can read off all the dispositions the particle has to move through 3-space in certain ways in various circumstances, ways dictated by the equations of the theory. Ψ, in other words, is equivalent to an infinite list of conditionals of the form 'If the particle is at $\underline{r}$, then it has these dispositions: ....'

This picture of things will seem objectionable to many, for it surely posits innumerable irreducible dispositions. To see this, consider the fact that the properties ascribed to a given particle by the associated state description, Ψ, do not supervene on the residue; the basic equations make it clear that fixing the position, velocity, and dynamically invariant features of the particle leaves an almost total latitude with respect to R and S. The dispositions a given particle has will thus only supervene on its categorical properties if it is the case that every Ψ is an eigenfunction of some complete set of commuting operators all of which represent categorical quantities. And this is surely not so. But if the dispositions of systems on this interpretation do not supervene on their categorical properties, then clearly there can be no sense in which the systems in question have their dispositions "in virtue of" their categorical properties.[52]

Irreducible dispositions, then, are a feature of this interpretive approach from the outset. In my view, this is no objection.[53] Now, however, we need to see how the approach extends to the many-particle case, especially because it is only when dealing with more than one particle that orthodox Bohm theory runs into the problem which this approach is intended to solve.

We might think, *prima facie*, that there will have to be a difference in the way in which the wavefunction at t, $\Psi(\underline{r}_1, \underline{r}_2,..., \underline{r}_N)$, ascribes dispositions to a given particle in the N-particle case, for we know that what particle 1 does next, say, will depend in part on the positions of the other particles at t. And we might account for this feature of things by stipulating that the dispositions which Ψ allots particle 1 depend not only on its own position, but on the positions of all the other N-1 particles. There is another, and perhaps more straightforward way of doing things, however. We can simply have Ψ assign dispositions to each particle of such a sort that the relevant circumstances for the manifestation of the dispositions involve positions for the other particles. That is, what Ψ says about particle 1 at $\underline{r}_1'$ (amongst other things) is that it has a disposition to move in such-and-such a way when the external circumstances external to system are so-and-so *and the positions of the other particles are* $\underline{r}_2'$, $\underline{r}_3'$,..., *and* $\underline{r}_N'$, *respectively*, a different disposition for the same external circumstances but with the other particles at $\underline{r}_2''$, $\underline{r}_3''$,..., and $\underline{r}_N''$, and so on. That may seem like a lot of dispositions, the set they make up

[52] The longer version of this paper contains a further elaboration of this line of thought.
[53] Again, I defend this stance in the longer version of the paper. See n. 26.

presumably has the same cardinality as the set of dispositions we had in the single-particle case; furthermore, if one is willing to individuate dispositions finely enough, there are no more dispositions here than we have in ordinary cases of, say, the solubility of a lump of sugar. (Think of the continuum of temperatures at which the sugar will dissolve.) What is more, we already have a very compact way of ascribing all those dispositions to each of the particles in the system -- namely, via the usual Ψ functions.

Assuming, then, that the sheer number of dispositions we end up ascribing to particles on this interpretation is not a problem, is there anything less than metaphysically innocent about the picture of quantum-mechanical systems it provides?

Unsurprisingly, nonlocality looms large. To put it briefly: if particle 1 has a lot of dispositions the manifestation of which depends not only upon (say) the local electromagnetic potential it experiences, but also on the positions of all the other particles in the system (particles 2 through *N*), then in order to decide what to do next at any given moment, so to speak, particle 1 has to know the location of the other particles at that moment.[54] It is tempting to conclude, then, that some of the causal factors which contribute to particle 1's manifesting the particular disposition it manifests at *t* by moving off in a particular way, some of the circumstances to which it responds thus, consist in other particles having certain distant locations at *t*. So this reworking of Bohm's theory has not eliminated its inherent appearance of nonlocality -- however exactly such an appearance should be understood.[55]

There is also an element of metaphysical novelty to this interpretation of QM, however. It is not clear to me what we should make of this feature of the interpretation, nor how uneasy it should make us. For present purposes, I mean only to illustrate the

[54] For an illustration of this aspect of the situation, see the treatment of the standard EPR-Bohm experiment sketched below.

[55] Although the world thus seems nonlocal according to both this version of the Bohm theory and the standard version, that is certainly not a peculiarity of these interpretive approaches. Note also that the language of the last paragraph suggests, accurately, that there must be a preferred frame in this interpretation, something which in tension with the dictates of special relativity as it is standardly understood. This is also a feature of the unreconstructed version of the Bohm theory.

feature in question by considering the way in which the interpretation treats the EPR-Bohm experiment, and a certain simple extension of that experiment.

There is more than one way of modelling spin along Bohmian lines. I will take the approach which derives from Bell and rework it along the lines of the dispositional reinterpretation of Bohm's theory described above.[56] So, first suppose that we have a single spin-half particle in an eigenstate of *x*-spin, and with a spatially localized wave-packet, approaching a Stern-Gerlach magnet oriented so as to measure spin in the *z*-direction:

The reinterpreted algorithm for determining the outcome of the measurement is as follows: If the particle is "in the top half of the wave-packet" (where, importantly, this locution is now to be understood only as a convenient shorthand for the statement of a purely mathematical condition on the relation between the particle's position coordinates and the structure of the mathematical object Ψ), it will have a disposition to move upwards on passing through the magnet. Otherwise, it will have a disposition to move downwards. An outcome results accordingly. So far, everything here is straightforward.

Now consider a pair of electrons in the spin singlet state, but nicely localized:

[56] Bell (1987), pp. 10-11. My presentation is deeply indebted to Albert's treatment in chapter 7 of his (1992); see esp. pp. 156-60.

Both Stern-Gerlach magnets are set to measure spin in the *z* direction. Now the reinterpreted algorithm ascribes a complex disposition, or a set of dispositions, to the particles as follows (bearing in mind the fact that talk about where a particle lies in a wave packet is, in the new interpretation, purely a convenient shorthand for getting at certain mathematical facts): The left-hand particle, particle 1, will go up if it lies in the top half of its wave packet, and down if it lies in the bottom half, *unless* particle 2 arrives at its magnet first, in which case particle 1 simply does the opposite of whatever particle 2 does, thus producing the familiar perfect anticorrelations. And particle 2 has just the same dispositions as particle 1, *mutatis mutandis*.[57]

Now of course the nonlocality of the interpretation is quite evident here, but that is not the feature to which I wish to draw attention. What is new here is that there is something peculiar about the dispositions each particle must have. Described abstractly, the peculiarity is this: Dispositions are normally thought of as dispositions to behave in certain ways in certain sorts of circumstances; and I think we usually assume that the sorts of circumstances in question can be specified in terms of their purely *qualitative* and *non-historical* features. For example, a soluble lump of sugar is disposed to dissolve when placed in water at a certain temperature. Which body of water it is placed in is irrelevant, insofar as there are no qualitative differences between bodies of (pure) water; and how the water was heated is equally irrelevant to the behaviour of the sugar, and unrelated to the disposition possessed by the lump, so long as it makes no difference to the way the water is when the sugar is placed in it.[58]

This general feature of dispositions, however, cannot carry over to the dispositions present in the EPR-Bohm experiment on the present interpretive approach.

[57] Note again the invocation of absolute time-ordering, even though the events are space-like separated. As noted, this is a feature which the dispositional interpretation inherits from standard Bohm theory.

[58] Apparent counterexamples from outside the quantum-mechanical realm to the general claim made here will, I think, disappear on closer inspection. My disposition to avoid people who have committed murder in the past, for example, is surely a disposition to avoid people who bear the present marks of such past actions when I (almost) encounter them, and so on.

The dispositions of the particles in the singlet-state pair must be either sensitive to what we might call "quantitative" facts (facts about which individuals it is that instantiate certain qualitative features),[59] or to historical facts (facts about what states of affairs obtained earlier, qualitatively described).[60]

To see this, consider a somewhat more complex four-particle variant on the usual two-particle EPR-Bohm experiment, with all magnets again set to measure spin in the *z* direction:

The idea here is simply that we have set up two ordinary two-particle EPR-Bohm experiments side by side, and then bent the paths of one particle from each pair so as to create the spatially symmetrical situation depicted. (The bending devices, let us suppose, have now been removed.) We thus have two pairs of particles each in the spin singlet state.[61]

[59] I am using the term 'quantitative' here in the sense in which it is used when we distinguish the quantitative from the qualitative identity of individuals.
[60] Dispositions to behave in certain ways in circumstances which are individuated in *both* historical and quantitative terms are also an option, but either sort will suffice on its own.
[61] In the appendix, I show that there is a perfectly anti-symmetrized four-particle state available to the particles with respect to which the present argument goes through in the same way.

Now, the interesting feature of this situation is as follows: Only one of particles 2 and 3 was produced at source 1 with particle 1, but on the interpretive approach we are considering, which one it was need not show up in any of the qualitative, non-historical features of the particles, or of the situation as a whole at the time depicted. Yet suppose, for example, that it is particles 1 and 2 which are produced together, and that on a certain run of the experiment, both particles are in the top halves of their wave packets. In this case particle 1 has (and must have, if the predictions of QM are to be reproduced) certain dispositions which tie it to particle 2: a disposition to move upwards if it arrives at an appropriately oriented Stern-Gerlach magnet before particle 2 does, and a disposition to move downwards if particle 2 reaches such a magnet first. No mention of particle 3 need be made in specifying dispositions ascribed to particle 1, on the other hand. In consequence, no characterization of the dispositions in question can be given in purely qualitative and non-historical terms.[62]

Conclusion

I have tried to highlight and clarify a set of intertwined issues which bring together certain debates at the heart of current work in the philosophy of QM , and some debates in general metaphysics which are rather longer in the tooth. In addition to setting out the way in which these issues arise, I have tried to illustrate the sort of unexpected twists and turns which can arise when we start to investigate the role which talk of dispositions plays, or could play, in various interpretations of QM. In particular, I hope

[62] On most runs of the experiment there will not be a perfect spatial symmetry to the situation: particles 2 and 3 may be opposite halves of their respective wave-packets, for example, or particle 2 may be nearer to particle 1 than particle 3 (or both). These asymmetries do not provide an escape route, however, for (holding the location of particle 1 at a certain point in the run fixed) if we give particle 1 the disposition to anti-correlate its behaviour to that of the particle which is uppermost, or nearest, say, there will always be other runs of the experiment on which particles 2 and 3 reverse roles, and on which particle 1 will in consequence be led astray. And in any case, there will be a set of cases (a measure-zero one, admittedly) in which perfect symmetry reigns.

to have shown that there may be some value in reinterpreting the formal structure of Bohm's theory in such a way as to exploit the central idea that the wavefunction can be read, in large part, as ascribing complex sets of dispositions to the system, or the parts of the system, whose state it is intended to represent. I have also shown, however, that the metaphysics of the resulting interpretation has some odd and intriguing aspects. Clearly, there is much more work of this sort to be done; but then, that is one of my main points.[63]

[63] For more on dispositions and the Bohm theory, but with different issues occupying centre stage and a very different approach to dispositions, see Pagonis and Clifton (1995).

References

Albert, D. (1992), *Quantum Mechanics and Experience*. Cambridge, Mass.: Harvard University Press.

Alston, W. P. (1978), "Dispositions, Occurrences, and Ontology," in R. Tuomela, ed., *Dispositions*. Dordrecht: D. Reidel, pp. 359-88.

Armstrong, D. M. (1968), *A Materialist Theory of the Mind*. London: Routledge & Kegan Paul.

Armstrong, D. M. (1973), *Belief, Truth and Knowledge*. Cambridge: Cambridge University Press.

Bell, J.S. (1987), *Speakable and Unspeakable in Quantum Mechanics*. Cambridge: Cambridge University Press.

Cartwright, N. (1989), *Nature's Capacities and their Measurement*. Oxford: Clarendon Press.

Dieks, D (1989), "Resolution of the Measurement Problem Through Decoherence of the Quantum State," *Physics Letters A 142*: 439-46.

Ghirardi, G. C., A. Rimini, and T. Weber (1986), "Unified Dynamics for Microscopic and Macroscopic Systems," *Physical Review D 34*: 470-91.

Goodman, N. (1983), *Fact, Fiction, and Forecast*. 4th ed. Cambridge, Mass: Harvard University Press.

Healey, R. (1989), *The Philosophy of Quantum Mechanics: An Interactive Interpretation*. Cambridge: Cambridge University Press.

Heisenberg, W. (1958), *Physics and Philosophy*. New York: Harper and Brothers.

Jammer, M. (1974), *The Philosophy of Quantum Mechanics: The Interpretations of Quantum Mechanics in Historical Perspective*. New York: John Wiley & Sons.

Lewis, D. (1997), "Finkish Dispositions," *Philosophical Quarterly 47*: 143-158.

Mackie, J. L. (1973), *Truth, Probability, and Paradox*. Oxford: Oxford University Press.

Margeneau, H. (1954), "Advantages and Disadvantages of Various Interpretations of the Quantum Theory," *Physics Today 7*: 6-13.

Martin, C. B. (1994), "Dispositions and Conditionals," *Philosophical Quarterly 44*: 1-8.

Martin, C. B. (1996), "How It Is: Entities, Absences and Voids," *Australasian Journal of Philosophy 74*: 57-65.

Mellor, D. H. (1974), "In Defence of Dispositions," reprinted in *Matters of Metaphysics*. Cambridge: Cambridge University Press, pp. 104-122.

Pagonis, C., and R. Clifton (1995), "Unremarkable Contextualism: Dispositions in the Bohm Theory," *Foundations of Physics 25*: 281-96.

Popper, K. R. (1957), "The Propensity Interpretation of the Calculus of Probability, and of Quantum Theory," in S. Körner, ed., *Observation and Interpretation in the Philosophy of Physics*. New York: Dover, pp. 65-70.

Popper, K. R. (1959), *Logic of Scientific Discovery*. London: Hutchinson.

Popper, K. R. (1982), *Quantum Theory and the Schism in Physics*. Totowa, NJ: Rowman and Littlefield.

Prior, E. (1985), *Dispositions*. Aberdeen: Aberdeen University Press.

Prior, E. W., R. Pargetter, and F. Jackson (1982), "Three Theses About Dispositions," *American Philosophical Quarterly 19*: 251-57.

Redhead, M. L. G, and P. Teller (1991), "Particles, Particle Labels, and Quanta: The Toll of Unacknowledged Metaphysics," *Foundations of Physics 21*: 43-62.

Ryle, G. (1949), *The Concept of Mind*. London: Hutchinson.

Teller, P. (1979), "Quantum Mechanics and the Nature of Continuous Physical Quantities," *Journal of Philosophy 76*: 345-61.

Teller, P. (1983), "The Projection Postulate as a Fortuitous Approximation," *Philosophy of Science 50*: 413-31.

Teller, P. (1995), *An Interpretive Introduction to Quantum Field Theory*. Princeton, NJ: Princeton University Press.

Thompson, I. J. (1988), "Real Dispositions in the Physical World," *British Journal for the Philosophy of Science 39*: 67-79.

Tooley, M. (1972), "Armstrong's Proof of the Realist Account of Dispositional Properties," *Australasian Journal of Philosophy 50*: 283-87.

van Fraassen, B. C. (1972), "A Formal Approach to the Philosophy of Science," in R. Colodny, ed., *Paradigms and Paradoxes*. Pittsburgh: University of Pittsburgh Press, pp. 303-66.

van Fraassen, B. C. (1980), *The Scientific Image*. Oxford: Clarendon Press.

van Fraassen, B. C. (1991), *Quantum Mechanics: An Empiricist View*. Oxford: Clarendon Press.

Appendix:

Anti-Symmetrizing the Double EPR Experiment

It is not difficult to see that there is a four-particle, fully anti-symmetrized state which yields the pattern of correlations between measurement outcomes on which the argument at the end of the section on the Bohm theory relies. Referring back to the diagram of the "double EPR" experiment, let us introduce the following notation:

(i) $| W >$ is a one-particle state vector corresponding to a spatial wavefunction localized just in front of SG_1 (the most westerly Stern-Gerlach device); similarly for $| N >$, $| S >$, and $| E >$, and SG_2, SG_3, and SG_4, respectively.[64]

(ii) $| + >$ and $| - >$ are the spin-space vectors for a spin-half particle which represent the two eigenstates of spin *z*.

Thus, for example, if the state vector for an electron is $| N > \otimes | + >$, or (employing a standard shorthand) $| N + >$, then the electron is localized just outside SG_2, and will with certainty produce a '+' outcome on subsequent spin *z* measurement.[65]

Moving now to consider states of the four-particle system, $| W + \ N - \ S - \ E - >$, say, is a vector on the four-particle Hilbert space, $H_1 \otimes H_2 \otimes H_3 \otimes H_4$, representing a state of the system in which the particle approaching SG_1 is destined to produce a '+' outcome whilst the other three produce the outcome '-'; let us represent such an outcome of the four measurements with the tuple $< + - - - >$. $| W + \ N - \ S - \ E - >$,

[64] Of course, it is a significant idealization to suppose that in such an experiment the four particles would be so highly localized. The cogency of the argument does not rely on the idealization in question, however. To make the relevant point we need only consider that range of cases in which the Bohmian particles are in fact contained in the region of space corresponding to these idealized spatial states.

[65] Note that such a vector does not count as a complete state specification on either the orthodox Bohmian approach or my reinterpretation; and, relatedly, note also that on both approaches, it is not only particles in the '+' eigenstate of spin *z* which are deterministically guaranteed to produce a '+' outcome on spin *z* measurement.

however, is not anti-symmetrized, and so is not, strictly speaking, a permissible state vector for the four-electron system; I mention it only to introduce the notation.

What we need, then, to run the argument in question, is a fully anti-symmetrized four-particle state in which (i) outcomes at SG_1 are perfectly anti-correlated with those at SG_2, say; (ii) outcomes at SG_3 are perfectly anti-correlated with those at SG_4; and (iii) there are no other correlations between outcomes at any of the other four pairs of measuring devices (namely: SG_1 and SG_3; SG_1 and SG_4; SG_2 and SG_3; and SG_2 and SG_4). To see how we can construct a vector representing such a state, first consider the fact that although neither

|W + N - S - E - >

nor

|N - W + S - E - >

is a permissible state vector, given symmetrization constraints, both represent a state of the system which would with certainty produce the result < + - - - >, *where the ordering of the elements of the tuple reflects the numbering of the measuring devices*, for in both cases the particle localized to the region corresponding to |W > (i.e., the particle which enters measuring device SG_1) is in the |+ > eigenstate of spin *z*, whilst the other three are in the |- > eigenstate.[66] Clearly, then, the same thing holds for any vector which is a permutation of |W + N - S - E - >.[67] It follows from this that any non-trivial[68] sum of

[66] This means, interestingly, that the numbers used to name the particles in the diagram do *not* in general correspond to the numbers labelling the four Hilbert spaces whose tensor product provides the state space for the four-particle system. There is thus a link here to the sorts of issues about the significance of the latter numbers raised by Redhead and Teller (1991) and by Teller (1995, ch. 2). (I leave aside the Fock space approach here; see Teller (1995, ch. 3).)

[67] Here and throughout I consider only permutations of "total particle states" -- i.e., of spatial-plus-spin states -- with one another, as those are the permutations we need to consider when imposing symmetrization constraints.

vectors which are permutations of $|W + \; N - \; S - \; E - \; >$ will represent a state in which the outcome $< + - - - >$ results with certainty. Thus, we need only consider the fully anti-symmetrized vector which can be written as a normalized and equally-weighted sum of such vectors i.e., that normalized and equally-weighted sum, $|\psi>$, which is such that $P_{ij} |\psi> \; = - |\psi>$, where i,j = 1, 2, 3, 4, and $i \neq j$) to have a permissible state description of a four-particle system which will, with certainty, produce the outcome $< + - - - >$ when all four devices are set to measure spin *z*. As that vector is a sum of 24 permutations of $|W + \; N - \; S - \; E - \; >$, I will not write it out in full here. However, the general expression for the anti-symmetrized vector corresponding to an arbitrary vector of the form $|\alpha \beta \gamma \delta>$, for distinct α, β, γ, and δ, leaving aside the normalization coefficient, is:

$$
\begin{aligned}
&|\alpha \beta \gamma \delta> - |\alpha \beta \delta \gamma> - |\alpha \gamma \beta \delta> + |\alpha \gamma \delta \beta> + |\alpha \delta \beta \gamma> - |\alpha \delta \gamma \beta> \\
&\quad - |\beta \alpha \gamma \delta> + |\beta \alpha \delta \gamma> + |\beta \gamma \alpha \delta> - |\beta \gamma \delta \alpha> - |\beta \delta \alpha \gamma> + |\beta \delta \gamma \alpha> \\
&\qquad + |\gamma \alpha \beta \delta> - |\gamma \alpha \delta \beta> - |\gamma \beta \alpha \delta> + |\gamma \beta \delta \alpha> + |\gamma \delta \alpha \beta> - |\gamma \delta \beta \alpha> \\
&\qquad\quad - |\delta \alpha \beta \gamma> + |\delta \alpha \gamma \beta> + |\delta \beta \alpha \gamma> - |\delta \beta \gamma \alpha> - |\delta \gamma \alpha \beta> + |\delta \gamma \beta \alpha>
\end{aligned}
$$

From here, construction of a state vector which will meet our needs is a relatively simple matter. Conditions (i)-(iii), given above, will be satisfied if we can construct a state vector which assigns a non-zero probability only to the outcomes

$$< + - + - >$$

$$< + - - + >$$

$$< - + + - >$$

$$< - + - + >$$

---

[68] I.e., any sum which does not produce the zero vector.

and which assigns equal weight to each of these. And that demand can be met by taking the vectors

$$|W+\ N-\ S+\ E->$$

$$|W+\ N-\ S-\ E+>$$

$$|W-\ N+\ S+\ E->$$

$$|W-\ N+\ S-\ E+>,$$

anti-symmetrizing each one in the fashion described with respect to $|W+\ N-\ S-\ E->$ above, thus yielding four 24-term sums of vectors which we dub

$$|\psi_{+-+-}>,\ |\psi_{+--+}>,\ |\psi_{-++-}>, \text{ and } |\psi_{-+-+}>,$$

respectively, and then letting

$$|\Phi> = \frac{1}{2}|\psi_{+-+-}> + \frac{1}{2}|\psi_{+--+}> + \frac{1}{2}|\psi_{-++-}> + \frac{1}{2}|\psi_{-+-+}>.$$

As $|\Phi>$ has 96 components of the north-south-east-west variety, I will of course leave its full expression as an exercise for the reader.