Against Quantum Indeterminacy[*]

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Abstract

A growing literature is premised on the claim that quantum mechanics provides evidence for metaphysical indeterminacy. But does it? None of the currently fashionable realist interpretations involve fundamental indeterminacy and the 'standard interpretation', to the extent that it can be made out, doesn't require indeterminacy either.

1 Introduction

The debate over the status of metaphysical indeterminacy has a number of fronts. Familiar battlegrounds include vague objects—clouds, mountains, heaps—and the 'open future.' More recently, it has been suggested that quantum mechanics (QM) provides a new reason to take metaphysical indeterminacy seriously. In particular, some have taken QM to threaten accounts that locate indeterminacy at the 'meta-level' (Darby, 2010; Skow, 2010; Calosi and Wilson, 2017). This debate presupposes that QM involves indeterminacy of a particular sort.[1] It is this presupposition that I wish to challenge.

One way of understanding metaphysical indeterminacy takes it to involve propositions with indeterminate truth-values. According to Barnes and Williams (2011), for instance, all states of affairs are perfectly determinate, it's just indeterminate which obtains. Another position, defended notably by Jessica Wilson (2013; 2017), holds that propositions have perfectly determinate truth-values, but allows for indeterminate states

[*]Forthcoming in *Thought*.

[1] One might think the sort of indeterminacy involved in QM is unique because it is *fundamental*. Unlike familiar cases of vagueness, the putative indeterminacy doesn't result from entities being composed of smaller constituents (Lewis, 2016, 75).

of affairs. For Wilson, a state of affairs is indeterminate just in case it involves an object having a determinable property without a unique corresponding determinate. For example, the color of an iridescent feather might be indeterminate because it is red from one perspective and blue from another; it has the determinable 'being colored' but multiple determinates of it. Another way for a state of affairs to be indeterminate is for an object to have a determinable but lack *any* determinate of it. Alleged examples of this 'gappy' form of indeterminacy occur in the context of QM.

My interest is not with this internal debate—one is free to adopt either understanding of metaphysical indeterminacy—but whether QM recommends such indeterminacy in the first place. Prima facie, it may seem obvious that it does. In classical physics, particles always have determinate positions and momenta. However, in QM position and momentum are incompatible observables; a sharp value of one precludes a sharp value of the other. For example, were one to measure precisely the momentum of a particle, its position would be maximally indefinite. Thus, there would seem to be indeterminacy with respect to the position of the particle in such a case. Such position indeterminacy is further suggested by images of electron clouds and position wavefunctions, which seem to suggest that in QM a particle's position can be 'spread-out.'

For one who adopts Wilson's approach to metaphysical indeterminacy, this situation can be understood as a particle with the determinable *position* but lacking a (unique[2]) determinate of position. If this is the correct understanding of QM, it follows that there is widespread indeterminacy at the fundamental level of reality.[3]

[2] For ease of exposition, I will drop this qualification in what follows. That is, I'll assume the 'gappy' version of indeterminacy (that there are no determinates) rather than the 'glutty' (that there are multiple determinates). However, there may be reasons to favor the glutty view (Calosi and Wilson, 2017).

[3] For our purposes here, I will treat QM as a fundamental theory. The status of indeterminacy in QM when viewed as a limiting case of quantum field theory (or some more fundamental theory) is beyond the scope of this paper.

2 Standard quantum mechanics

So, is this the correct understanding of QM? Obviously the interpretation of QM is an area of deep disagreement and well-entrenched camps. However, *none* of the three most popular realist interpretations involve indeterminacy of this sort.

First, and most straightforwardly, the Bohm theory endows particles with determinate positions and momenta at all times. While it's possible that other properties (e.g., spin) may lack determinate values, position is the only *fundamental* feature of Bohmian particles. Second, the Everett interpretation, as developed by Wallace (2012), recognizes only the universal wavefunction in its fundamental ontology. The universal wavefunction is perfectly determinate at every time and evolves deterministically according to Schrödinger's equation. As with Bohm, there may be indeterminacy or vagueness that enters in at the level of emergent ontology (e.g., particles, worlds, persons), but not at the fundamental level. Finally, consider dynamical collapse theories such as versions of GRW. The two versions of GRW adopted by most contemporary defenders are the mass-density and flash ontology varieties. Neither contains fundamental indeterminacy: the distribution of mass-density and the location of the flashes are both perfectly determinate. Unlike the other two interpretations, GRW is *indeterministic*, and as such, may involve indeterminacy about the future. However, (a) this requires substantive assumptions about the metaphysics of time and (b) any indeterminacy involved isn't particularly novel—it's a generic feature of any indeterministic theory.

So, what interpretation of QM do advocates of quantum indeterminacy have in mind? The usual reply is the 'standard', 'orthodox' or 'Copenhagen' interpretation.[4] It's not entirely clear what's meant by these labels, but the view in question seems to involve the following three principles:[5]

[4] "In keeping with the current literature on this topic, I shall consider here only the standard interpretation of quantum mechanics (sometimes referred to as the 'orthodox' or 'Copenhagen' interpretation)" (Bokulich, 2014, 460–461). See also Wolff (2015, 380), Wilson (2017, 105).

[5] As noted by Wallace (2016), what follows is a familiar way of characterizing QM in the philosophy

Eigenstate-eigenvalue link: A system A has a value v of property P iff the quantum state of A is in an eigenstate of of the associated operator $\hat{O}$ with eigenvalue $= v$.

Measurement postulate: A measurement of A collapses the quantum state of A into an eigenstate of $\hat{O}$ with a probability of $|\Psi|^2$.

Schrödinger dynamics: When unmeasured, the quantum state of A evolves according to the Schrödinger equation.

These three principles suggest a dual ontology of quantum states and physical properties ('observables'). As stated, standard QM makes no claims about the relative fundamentality of these categories, but if it is to suit the needs of the advocate of metaphysical indeterminacy, physical properties cannot be ontologically derivative. This may seem odd given that the properties are ascribed on the basis of the quantum state, via the eigenstate-eigenvalue link. However, there are at least two ways to make sense of this. First, one can advocate a flat ontology for standard QM. Typically, presentations of the view don't specify a fundamental ontology and some may be skeptical of fundamentality talk in general. The flat view holds that quantum states and physical properties are on equal footing ontologically. Second, one can view the quantum state non-ontologically. A familiar position takes the physical significance of quantum states to consist in what they tell us about physical properties (see section 4.4). If, by contrast, one took the properties to be ontologically derivative and quantum states to be fundamental, there would be little room for metaphysical indeterminacy. Like the contemporary Everett interpretation, any indeterminacy would occur at the non-fundamental level and hence may be viewed as eliminable. Thus, charity recommends consideration of a version of standard QM in which physical properties are non-derivative.[6]

of physics. But, as Wallace argues at length, this understanding does not seem to capture the version of QM assumed by working physicists. Nor does it obviously capture the views of Bohr, with whom the Copenhagen interpretation is most closely associated (Halvorson and Clifton, 2002). I refer to this view as 'standard QM' to avoid these connotations as much as possible.

[6] I thank an anonymous referee for pressing me on this point.

3 Quantum indeterminacy

According to standard QM—as captured by the three principles above—there will be many situations in which particles lack determinate properties. For example, the case in which one performs a precise momentum measurement will leave the particle in a quantum state that is not an eigenstate of the position operator.[7] Hence, the Wilson-style analysis of this case attributes to the particle the determinable of *position* but not the corresponding determinate.

However, only the latter claim—that the particle lacks determinate position—follows from the principles of standard QM. Moreover, the inference from lacking a determinate value of P to having an *indeterminate* value of P is not valid in general. For example, the British Museum doesn't have a (determinate) house number on Great Russell street.[8] Does this mean its house number is indeterminate? Surely not. It simply doesn't have one. This suggests another understanding of standard QM, which I'll call the *sparse view*.

Sparse view: when the quantum state of A is not in an eigenstate of $\hat{O}$, it lacks *both* the determinate and determinable properties associated with $\hat{O}$.

I claim that the sparse view is no less plausible than the version of standard QM presupposed by advocates of quantum indeterminacy.

[7] Strictly speaking, there are no eigenstates of the position operator in QM because position is continuous (i.e., has a continuous spectrum). In what follows, I will ignore this and treat position as discrete for the benefit of those who defend quantum indeterminacy. The arguments below could equally well be made in the context of a genuinely discrete-spectrum observable such as spin, but the case for indeterminacy appears most forceful when put in terms of position.

[8] The full address of the British Museum is: Great Russell Street, London WC1B 3DG.

4 Objections to the sparse view

4.1 Position and existence

In her defense of quantum indeterminacy, Bokulich claims that "...despite the inability to ascribe a position to the particle, the existence of the particle is never in question" (2014, 465, n.35). This suggests that the determinable *position* is required for existence. There are at least three replies to this objection. First, the particle in question will have other properties when it isn't in a position eigenstate. For instance, it will possess determinate state-independent properties like mass and charge as well as any other properties corresponding to observables in which it is in an eigenstate. The possession of such properties may be sufficient for existence.

Second, we may regard the particle as determinately located in a *region* of space. This is the case whether the particle is confined to a small region—as in the case of an infinite square well—or even if its wavefunction is spread over the entirety of space (here the region in question is all of space). In either case, there will be some operator of which the system is in an eigenstate, and which corresponds to a determinate way of being in the region R. For instance, the particle may be in a particular superposition of several positions, all of which are included in R. In such a case, it is natural to ascribe it the property of "being in region R."[9]

Third, it is not obvious why possessing only the determinable *position* makes the existence of the particle any less mysterious. Return to the case of the British Museum. Suppose an American tourist believes that having an address requires having a house number. If the tourist were then told that the British Museum has the determinable *house number*, but lacks any determinate house number, it seems they would still take it to lack an address. Similarly, it's not clear why having *position*, without a determinate position, is any consolation for one who thinks an object must have a position to exist.

[9] I return to this point in the next section.

4.2 Superpositions and determinables

The next line of objection draws on the fact, noted above, that particles will be in an eigenstate of an operator associated with being in a given *region* of space. Isn't this property—being located in a region—just the determinable with the precise locations in the region as determinates? If so, then standard QM would seem committed to bare determinables. The problem with this objection is the supposition that quantum superpositions are associated with determinables.

Consider a simplified version of a particle in an infinite square well in which there are only two maximally-precise locations possible for the particle, x_1, x_2. If we measure the particle's momentum precisely, its position state will not be in an eigenstate of x_1 or x_2, but rather, in a superposition of the form $C_0|x_1\rangle + C_1|x_2\rangle$, where C_i is a complex number. There will be an operator associated with any such superposition, and the system will be in an eigenstate of that operator. It follows from the eigenstate-eigenvalue link that we should ascribe the system a property, but is this property the determinable with being located at x_1 and being located at x_2 as determinates?

There are several reasons why not. First, the property in question will not behave like an ordinary disjunction. It can be true that a particle possesses it, but false that the particle possesses either of the disjuncts. Of course, this is to be expected given that Wilson's view allows for bare determinables. But, it has other features that seem at odds with determinables. It contains a *weighting* of the components (x_1, x_2) given by the complex numbers and connected to probabilities of measurement outcomes by the Born rule. Perhaps most significantly, the superposition is *inconsistent* with the particle being in an eigenstate of the relevant operator. Thus, upon measurement, the system would simultaneously lose a determinable and gain a determinate of it.

Calosi and Wilson acknowledge this problem in a footnote.

> It would be convenient if the determinable in a case of superposition [meta-

> physical indeterminacy] could be seen as the property of being in the superposition state, but this would violate the assumption that determinables of a determinate 'stick around' when determined. (2017, 17, n.16)

However, the problem is worse than they suggest. The property in question—whatever we choose to call it—is attributed on the basis of the system being in an eigenstate of an observable associated with a certain superposition (as per the eigenstate-eigenvalue link). After a measurement this is no longer the case, and hence, QM provides no basis for thinking it still has the property. The indeterminist might claim that having a determinate entails having the corresponding determinable, but (a) they have already denied the inference in the other direction and (b) the determinable so entailed is not the same property as that associated with a particular superposition state. As suggested above, one could think of a distinct determinable (e.g., 'being located in the well') of which the superposition property is a determinate, but this wouldn't help establish the claim that the superposition property is itself a determinable.

There are further features of superpositions that make them unsuited to ground attributions of determinables. Consider the case of spin in two orthogonal directions x and z. A particle in an eigenstate of x-spin will also be in a superposition of z-spin; we've just described the same quantum state using two different bases. But, on the present proposal, this would mean that having a determinate value of x-spin entails having a determinable, not of x-spin, but of *z-spin*. Some amount of revision is tolerable in our understanding of the relation between determinables and determinates, but at a certain point, the concepts have been stretched to the point at which they are no longer helpful.

So, how can the sparse view deny the inference from superpositions to determinables? On the sparse view, one must recognize that a system has a property associated with being in a given superposition. But, one needn't regard the relation of this property to those associated with the components of the superposition as that of determinable to determinate. In the simplified position case, the sparse view holds that the property of being in a superposition of x_1, x_2 is a *determinate* property that is *nomologically* related to the properties of being located at x_1 and being located at x_2 via the Born rule. This is all that's required by standard QM.[10]

4.3 Entanglement

This objection takes inspiration from a case given by Bokulich. Suppose we entangle the positions of two particles A, B such that their joint state is an eigenstate of $|x_A - x_B|$ but not x_A nor x_B taken individually. In such a case, "...even though particle A is not in an eigenstate of the position operator, we can still say something meaningful about that particle's position, namely that it is 10 meters away from particle B" (Bokulich, 2014, 470, n.46). The thought, I take it, is that particles must have *position* to bear distance relations.

There are two ways for the advocate of the sparse view to reply. The first appeals to a well-known position that denies this claim: Leibnizian relationism, according to which material bodies bear distance relations to one another but lack absolute positions. Taking this up, one could grant that the particles bear the distance relation—in virtue of being in an eigenstate of the associated observable—but nevertheless lack individual positions, even indeterminate ones. This involves rejecting the supposition implicit in this Bokulich's challenge that a difference-in-quantity relation requires the relata to possess (the determinable of) the quantity. But the denial of such a principle is implicated by other views (e.g., comparitivism about quantity (Dasgupta, 2013)) and suggested by other examples (e.g., gauge potentials (Healey, 2007)). Thus, the sparse view can grant that we can say something about relative positions of the particles in such a state without being committed to their having positions.

[10] On the sparse view, one is free to recognize general determinables that follow from the more specific superposition properties licensed by the eigenstate-eigenvalue link. For example, if the particle is in the state $\frac{1}{\sqrt{2}}(|x_1\rangle + |x_2\rangle)$ then one may regard it as located in the region $x_1 \cup x_2$ in virtue of possessing the property P associated with the equally-weighted superposition of x_1, x_2. The crucial point is that P itself is not to be identified with the more general determinable, but rather is a *determinate* of it, as are the properties associated with differently-weighted superpositions and the pure states $|x_1\rangle, |x_2\rangle$.

A second strategy of reply is to deny that the property in question should be thought of as a distance relation between A and B. The system in an eigenstate is the joint AB system, not the individual particles. The joint system will be in an eigenstate of the operator associated with a superposition of states, each of which is an eigenstate of particle positions bearing the relevant distance relation, but we've seen that the association of superpositions with determinables is problematic. Thus, in this case, an advocate of the sparse view could maintain only that the joint AB system possesses a determinate property, which nomologically entails that any measurement of A and B will find them 10 meters apart.[11]

4.4 Collapse

Finally, it might be thought that the sparse view fails to do justice to the physical understanding of wavefunction collapse in standard QM. According to the measurement postulate, the act of measurement causes the wavefunction of the system to collapse into an eigenstate of some operator; this certainly seems like the value of the associated observable going from indeterminate to determinate. First, while a full investigation would be required to settle the matter, a quick look at textbook expositions of standard QM suggests it is equivocal between this understanding of collapse and one in which measurement brings about new properties.[12] It is certainly not the case in general that determinables precede determinates. If the UK government decided all addresses must have a house number and one was assigned to the British Museum, then it would come

[11] Consider the case of spin. On the present proposal, the sparse view claims that for a compound system in the singlet state $\frac{1}{\sqrt{2}}(|\uparrow_A\rangle|\downarrow_B\rangle - |\downarrow_A\rangle|\uparrow_B\rangle)$ the eigenstate-eigenvalue link licenses the attribution of a *determinate* property associated with that particular superposition, from which it follows that the spins of A and B along a given axis will be found to be opposite with probability $= 1$. As noted above (fn. 10), one could also recognize a more general determinable—'containing particles with opposite spins'—of which this property is one among several possible determinates (including, e.g., the property associated with $|\uparrow_A\rangle|\downarrow_B\rangle$).

[12] Indeed, sometimes the ambiguity appears within a single exposition: "An electron may occur in a state in which its position is indeterminate. So it simply does not have a precise position, rather like a cloud... The electron had no position but, during the measurement process, it was compelled to respond to a question that had no predetermined answer..."(Gisin, 2014, 44).

to have the relevant determinable and determinate simultaneously.

More broadly, it's worth emphasizing that standard QM is generally associated with a view of the wavefunction as primarily *probabilistic* as opposed to *ontological*.[13] On this understanding, the wavefunction may allow one to ascribe a property—when it's in an eigenstate of some observable—but when it is 'spread-out' with respect to some observable, one should resist the urge to view the particle itself (or its properties) as being similarly fuzzy. Rather, the spread-out wavefunction serves only to inform us about what we should expect to find upon measurement, at which time we will be able to ascribe determinate properties to the particles. If this is the right way to think of standard QM, to view collapse as a transition from indeterminate to determinate isn't in line with its non-ontological view of the wavefunction.

5 Examples

To illustrate the difference between the two views of standard QM on offer—one that involves Wilson-style indeterminacy and the sparse view—let's briefly consider two familiar cases.

5.1 Schrödinger's cat

In the Schrödinger cat scenario, we suppose the system (ignoring all other degrees of freedom) is in a superposition of the form: $C_0|alive\rangle + C_1|dead\rangle$, where *alive* and *dead* are the states associated with the cat being alive and dead, respectively. On the inde-

[13] This is not to assume that the probabilities involved must be viewed subjectively. The point is rather that the primary role of the wavefunction (when it's not in an eigenstate of $\hat{O}$) is to tell us the probabilities associated with a hypothetical measurement on the system, either by reflecting our credences or by representing the objective chances. This should be distinguished from views according to which the wavefunction is a physical field or a sui generis element of ontology. Taking the wavefunction to represent objective chances may involve a certain form of indeterminacy insofar as it is indeterminate what properties the system will be found to have upon measurement, but as mentioned above (with respect to GRW), such indeterminacy is a generic feature of indeterministic theories and is closely related to debates over the 'open future'.

terminacy view, the cat has the $alive/dead$[14] determinable, but no determinate of being alive or being dead. This is why it is appropriate to say that it is indeterminate whether the cat is alive or dead until we look in the box, which seems to capture the familiar images of a ghostly cat somewhere between life and death.

Now, the sparse view *agrees* that (a) the cat is neither determinately alive nor determinately dead and (b) it is (determinately) in a superposition of alive/dead. It denies only that the property associated with being in an alive/dead superposition is a *determinable* with being alive and being dead as determinates. The advocate of the sparse view asks why we should invoke the determinable/determinate relation in this context, when the behavior of superpositions and their components is not well-modeled by that relation.

5.2 Two-slit experiment

In the two-slit experiment, we consider a source that emits one particle at a time in the direction of two narrow slits, beyond which lies a detection screen. Surprisingly, the collection of detections of the screen reveals interference effects, even though there would seem to be nothing to interfere given that only solitary particles pass through the device. Consider the observables associated with passing through slit 1 and slit 2, respectively. If a particle passing through the device is unmeasured (before it arrives at the screen), it will be in a superposition of the form $C_0|slit1\rangle + C_1|slit2\rangle$. On the indeterminacy interpretation, the particle possesses the $slit1/slit2$ determinable, while lacking either of its determinates. On the sparse view, the particle possesses the determinate property associated with being in a particular superposition of $slit1/slit2$, which is not a determinable with 'passing through slit 1' and 'passing through slit 2' as determinates.

Now, it might seem that the indeterminacy view has an advantage in this case . We might wonder how it is that a particle can get from the source to the screen without

[14] Calosi and Wilson (2017) call it "having a certain life status."

passing through one of the slits. The indeterminist can claim that possession of the *slit*1/*slit*2 determinable accounts for this, and so, the sparse view's failure to recognize such a determinable is a real cost.[15] However, it's not clear what possession of the property associated with the superposition in question is supposed to tell us about the trajectory of the particle. Indeed, standard QM is often taken to reject the idea of particle trajectories altogether, in which case it's hard to see *how* we can view the property in question as a determinable with 'going through slit 1' and 'going though slit 2' as determinates. Again, the invocation of a determinable does little to unmuddy the waters.

6 Conclusion

QM, then, shouldn't trouble those who reject metaphysical indeterminacy. None of the currently fashionable interpretations involve fundamental indeterminacy, and 'standard' QM admits of a version—the sparse view—free from indeterminacy. While QM is *compatible* with metaphysical indeterminacy, there is no independent reason to prefer an interpretation that contains it *even if one adopts standard QM.* This means the debate over metaphysical indeterminacy is advanced little by consideration of QM. Fans of fundamental indeterminacy might look to QM for guidance about its nature, but those who deny it needn't worry that they have to adopt a non-standard interpretation of QM to save their position. Indeed, it is the *defender* of quantum indeterminacy who must adopt a specific version of 'standard' QM with little independent motivation.

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[15] Indeed, Calosi and Wilson (2017), call the determinable in question "having traveled from the emitter to the detector."

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