WAVE FUNCTION ONTOLOGY

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April 19, 2001

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Abstract

I argue that the wave function ontology for quantum mechanics is an undesirable ontology. This ontology holds that the fundamental space in which entities evolve is not three-dimensional, but instead $3N$-dimensional, where N is the number of particles standardly thought to exist in three-dimensional space. I show that the state of three-dimensional objects does not supervene on the state of objects in $3N$-dimensional space. I also show that the only way to guarantee the existence of the appropriate mental states in the wave function ontology has undesirable metaphysical baggage: either mind/body dualism is true, or circumstances which we take to be logically possible turn out to be logically impossible.

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> "While our theory can be extended formally in a logically consistent way by introducing the concept of a wave in a 3N-dimensional space, it is evident that this procedure is not really acceptable in a physical theory..." (Bohm 1957, 117)

1. Introduction

A central reason philosophers are interested in quantum mechanics is that quantum mechanics seems to tell us surprising things about the nature of the world. For example, quantum mechanics has been used as a premise of arguments which purport to show that the world is indeterministic, that the world is nonlocal, and even that there are multiple worlds. These arguments are contentious, but they have been much discussed in the contemporary philosophy of physics literature.[1]

There is another surprising claim that has been asserted to follow from quantum mechanics which has *not* been much discussed in the contemporary literature. This claim is that the fundamental space in which entities evolve is not three-dimensional, but instead 3*N*-dimensional, where *N* is the total number of particles standardly thought to exist in the three-dimensional universe. I will call proponents of this claim proponents of the *wave function ontology*. David Albert, for example, advocates this ontology:

> the space *we* live in, the space in which any realistic understanding of quantum mechanics is necessarily going to depict the history of the world as *playing itself out* ... is *configuration*-space. And whatever impression we have to the contrary (whatever

> impression we have, say, of living in a three-dimensional space, or in a four-dimensional space-time) is somehow flatly illusory. (Albert 1996, 277)

Albert's reason for espousing this ontology is, roughly, that the wave function is a fundamental part of quantum mechanics, and the wave function evolves in 3*N*-dimensional space.

The exact formulation of the wave function ontology depends on what version of quantum mechanics is under consideration. A proponent of the wave function ontology who believes a dynamical reduction theory such as the GRW theory[2] would believe that the wave function field is all that exists – that is, all that exists is a 3*N*-dimensional space with a field evolving in that space, where the field value for each point in the space is given by the wave function. A proponent of the wave function ontology who believes in Bohm's interpretation,[3] in contrast, would believe that, in addition to the wave function field evolving in the 3*N*-dimensional space, a universal particle also evolves in that space.

I will argue in this paper that the wave function ontology is an undesirable ontology for quantum mechanics.[4] Instead of the wave function ontology, there are two other types of ontologies one could endorse. A proponent of a *three-dimensional* ontology would deny the existence of the wave function, and would only endorse the existence of objects evolving in everyday three-dimensional space. A proponent of a *mixed* ontology would hold that, in addition to the 3*N*-dimensional space, there also exists a three-dimensional space. (One could hold that both these spaces are hypersurfaces in a (3*N*+3)-dimensional space.)

2. On the Correspondence Between Three-Dimensional Space and 3*N*-Dimensional Space

Some might claim that there is no real difference between the mixed ontology and the wave function ontology, since the state of three-dimensional objects *supervene*s on the state of the wave function (and perhaps other objects) in 3*N*-dimensional space. For example, they would say that "the cat is in the box" is true if and only if the objects in 3*N*-dimensional space are in an appropriate state.

The description of what constitutes 'an appropriate state' would depend on what version of quantum mechanics is under consideration. Proponents of the claim that there is no real difference between the mixed ontology and the wave function ontology would say that on dynamical reduction theories, "the cat is in the box" is true if and only if the wave function is such that the accessible mass of the cat is located within the accessible mass of the box (assuming that they endorse the Ghirardi et. al. 1995 interpretation of dynamical reduction theories).[5] Also, proponents of the claim that there is no real difference between the mixed ontology and the wave function ontology would say that on Bohm's interpretation, "the cat is in the box" is true if and only if the universal particle is in the region of 3*N*-dimensional space which corresponds to the *N* particles being arranged in three-dimensional space in such a way that the cat-particles and the box-particles are such that the cat is in the box.

As I will now show, the claim that the state of objects in three-dimensional space supervenes on the state of objects in 3*N*-dimensional space is incorrect. One could give a philosophical argument against this claim by questioning the very idea that, starting from a fundamental reality of objects evolving in a 3*N*-dimensional space, one can truly describe the evolution of objects in a three-dimensional space. One could argue that since there is no three-dimensional space in fundamental reality, there is no three-dimensional space at all, and hence it is incorrect to talk of the state of objects in three-dimensional space supervening on the state of objects in 3*N*-dimensional space.

While I am sympathetic to this sort of argument, I believe that it would quickly lead to deep and potentially unresolvable issues best saved for another paper. Instead, I will argue that, even assuming that it is possible for the state of objects in one space to supervene on the state of objects in another space, for the case of quantum mechanics this supervenience does not hold. There are many different ways that *N* particles could evolve in three-dimensional space which are all compatible with a particular evolution of objects in 3*N*-dimensional space. I will now give my basic argument for this anti-supervenience claim; I will consider important objections to this argument in the next two sections.

The reason there is no supervenience is that nowhere in the 3*N*-dimensional space is it specified which dimensions correspond to which particles. It could be that the *x*, *y*, and *z* coordinates of particle number 3 in the three-dimensional space correspond to the seventh, eighth, and ninth dimensions[6] of the 3*N*-dimensional space, or it could be that they correspond to the ninth, eighth, and seventh dimensions, or it could be that they correspond to the 30^{th}, 25^{th}, and 240^{th} dimensions, and so on. These different correspondences entail different ways that the *N* particles evolve, given a particular evolution of the objects in the 3*N*-dimensional space. Note that the difference between these correspondences is not just haecceitistic; relations like the distance between particles would be different depending on which correspondence were chosen. Thus, there is a many-to-one correspondence between three-dimensional spaces with *N* particles and a 3*N*-dimensional space; given the state of the objects in 3*N*-dimensional space, one cannot establish the state of the objects in three-dimensional space.[7]

As an example, consider Bohm’s interpretation. On the mixed ontology, there exist both a three-dimensional space with N point particles and a $3N$-dimensional space with a wave function field and a universal particle. The evolution of the universal particle represents the configuration-space evolution of the N particles. It is not the case, however, that given just the evolution of the universal particle, one could determine the evolution of the N particles. Following the argument in the previous paragraph, it could be that the x, y, and z coordinates of particle number 3 in the three-dimensional space correspond to the seventh, eighth, and ninth coordinates of the universal particle, but it could be that they correspond to different coordinates.

In sum, the state of the objects in three-dimensional space does not supervene on the state of the objects in $3N$-dimensional space. This shows the radically revisionary nature of the wave function ontology: our everyday claims, such as that the world has just three extended spatial dimensions, and that there are three-dimensional objects like boxes and cats, turn out to be *false* on the wave function ontology.

One could maintain, in reply to the above argument, that, for each possible correspondence between a three-dimensional space and the $3N$-dimensional space, a three-dimensional space supervenes on the $3N$-dimensional space, with that correspondence. This proposal, though, entails that there are some three-dimensional spaces where the cat is in the box, and others where there is nothing recognizable as a cat or a box at all. Since no three-dimensional space would be privileged over any other, everyday claims like "the cat is in the box" would still be false.

3. The Hamiltonian Does Not Determine the Correspondence

An argument of David Albert's can be taken as an objection to my argument above. Albert argues that the *Hamiltonian* of the equation of motion for the wave function determines in what way the objects in 3*N*-dimensional space represent a (hypothetical) world with multiple particles. He writes:

> a quantum-mechanical world with [one sort of Hamiltonian] will appear to its not-too-closely-looking inhabitants to have *two* dimensions, and ... a quantum-mechanical world with [another sort of Hamiltonian] will appear to *its* not-too-closely-looking inhabitants (just as *our own* does) to have *three*. (Albert 1996, 282)

Albert's argument for this is as follows. Suppose that the wave function ontology is true, and suppose that the Hamiltonian for the wave function is one which would describe a normal sort of interaction between *N* particles in a three-dimensional space. Albert writes that, given such a Hamiltonian,

> *one particular* hypothesis about the number of physical dimensions this space actually has, about the number of distinct material particles which are actually floating around *in* it, can be distinguished as uniquely natural and reasonable and elegant and whatever else you might like: the hypothesis that we are looking at a *three*-dimensional space, in which [*N*] distinct material particles are floating around; the hypothesis (that is) that the potential terms in this Hamiltonian represent an interparticle force whose intensity depends on the *distance* between the particles in question. (Albert 1996, 280-1)

Albert's conclusion is that the quantum Hamiltonian determines that the world appears three-dimensional to its inhabitants, even though such appearances are nonveridical.

What should we make of this argument that a world with the wave function ontology and a certain sort of Hamiltonian will falsely appear to its not-too-closely-looking inhabitants to have three dimensions? I maintain that the argument is unconvincing. Consider objects such as a wave function field evolving in a 3*N*-dimensional space. As I have shown, there are multiple ways that this space can correspond to a three-dimensional space. Now, what Albert has correctly pointed out is that the Hamiltonian for the system could be such that *one particular way* that the universal particle corresponds to a world with multiple particles gets uniquely picked out by a criterion of naturalness. What makes that way uniquely natural is that, on *that* correspondence, the potential terms in the Hamiltonian represent an interparticle force that depends on distance between the particles, while on any other correspondence, the potential is a very unusual one, where the potential terms cannot be interpreted as representing any everyday force.

The problem with Albert's argument can be briefly stated but is, I believe, decisive. The problem is that the naturalness of the correspondence does not get us anywhere. It isn't the case that we can select the natural correspondence and forget about the rest; since there is no three-dimensional space, each correspondence is equally real, or (if you prefer) equally unreal. To say that one correspondence is natural is to make an epistemic claim about how we judge correspondences. There is no ontological import to that claim.

Perhaps though there is some aspect of the ontology of the 3*N*-dimensional space which uniquely selects a correspondence. Such a proposal will be considered in the next section.

4. Physical Facts Do Not Determine the Correspondence

The second objection I will consider to my argument runs as follows. I have been assuming that there is nothing intrinsic to the 3*N*-dimensional space which picks out a particular correspondence to three-dimensional space. Albert implicitly goes along with this assumption, because he suggests that one correspondence is preferred on grounds of naturalness or reasonableness; he does not appeal to an intrinsic fact about the world which picks out a certain correspondence. (If such an intrinsic fact existed, it would be possible for the fact to pick out an unnatural correspondence, but Albert rules out unnatural correspondences.) The second objection is that, contrary to Albert's and my assumption, there *is* some intrinsic fact about the $3N$-dimensional space which specifies how that space corresponds to a three-dimensional space.

The problem with this objection is that there could not be such a fact. Since there is no three-dimensional space with multiple particles, there cannot be any facts of the form: "the seventh, eighth, and ninth dimensions of the $3N$-dimensional space correspond to the x, y, and z coordinates of particle number 3 in the three-dimensional space." It does not help to have a fact of the form: "the seventh, eighth, and ninth dimensions of the $3N$-dimensional space *would* correspond to the x, y, and z coordinates of particle number 3 in three-dimensional space, were such a space to exist." Since such a space does not exist, the fact has no ontological import.

One might attempt to appeal to the intrinsic properties (such as mass, charge, and spin) of the (hypothetical) N particles as represented in the $3N$-dimensional space, and suggest that these properties establish a unique correspondence. One might also attempt to appeal to the facts about identical particles: quantum mechanics guarantees, for example, that the wave function is such that all particles which are bosons of the same type are in the same quantum state. None of this is enough, however, to establish a unique correspondence. In the best-case scenario, the following two claims will hold. (1) The intrinsic properties establish that the first, second, and third dimensions (say) of the $3N$-dimensional space correspond to particle number 1 in the three-dimensional space, and so on for each particle. (2) If it is established that, for example, the first, second, and third dimensions of the $3N$-dimensional space correspond to the x, y, and z coordinates of particle 1 of bosonic type α, then it will be established which dimensions of the $3N$-dimensional space correspond to which coordinates for each particle of type α. But even assuming this best-case scenario, the following two correspondences are still possible: in correspondence A, the first, second, and third dimensions of the $3N$-dimensional space correspond to the x, y, and z coordinates of particle 1 of type α, and the fourth, fifth, and sixth dimensions correspond to the x, y, and z coordinates of particle 2 of type β; while in correspondence B, the first, second, and third dimensions correspond to the x, y, and z coordinates of particle 1, and the *sixth*, *fifth*, and *fourth* dimensions correspond to the x, y, and z coordinates of particle 2. These different correspondences involve real differences: distance relations between the particles would be different depending on which correspondence is selected.

5. Mental States in 3*N*-Dimensional Space

The objections considered above do not affect my argument, so I conclude that there is no single state of the objects in three-dimensional space which supervenes on the state of the objects in $3N$-dimensional space. I also maintain that this shows that the wave function ontology is radically revisionary, since everyday claims like “the cat is the box” turn out to be false. Is this enough to show that the wave function ontology is an untenable ontology for quantum mechanics?

I am willing to grant that the answer is “no”. A necessary criterion for a tenable ontology is that the ontology not affect the empirical predictions of the theory. One might think that I have already shown that this criterion is violated by the wave function ontology, but I would disagree. Empirical predictions of a theory are, at their fundamental level, predictions about what phenomenal experiences observers would come to have.[8] If the wave function ontology can leave unaffected the predictions made by quantum mechanics concerning phenomenal experiences of observers, then the wave function ontology meets this criterion for a tenable ontology.

Does the wave function ontology affect the predictions concerning phenomenal experiences of observers? On the mixed ontology, when the objects in 3*N*-dimensional space are in a certain state, a cat will be in a box in the three-dimensional space, and ideal observers will have the phenomenal experience of the cat being in the box. But on the wave function ontology, the proposition that the cat is in the box is false, so there is prima facie no reason to think that ideal observers will have the phenomenal experience of the cat being in the box.

I will now consider a proposal which can guarantee that, on the wave function ontology, observers have the appropriate phenomenal experiences. Instead of the proposal of the previous section, where a physical fact picks out a correspondence between the objects in 3*N*-dimensional space and the objects in three-dimensional space, this proposal is that there is a *psychophysical* fact which picks out a correspondence between the objects in 3*N*-dimensional space and *mental states*. This psychophysical fact is of the form: "the mental states which supervene on the state of a world where the wave function ontology is true are the same as the mental states which *would* supervene on *N* particles in three-dimensional space (or *N* particles in three-dimensional space and the physical objects in 3*N*-dimensional space), *were* those *N* particles to evolve in such a way that the following correspondence holds between the state of the physical objects in 3*N*-dimensional space and the *N* particles: the x, y, and z coordinates of particle number 1 in the three-dimensional space correspond to the first, second, and third dimensions of the 3*N*-dimensional space; the *x*, *y*, and *z* coordinates of particle number 2 in the three-dimensional space correspond to the fourth, fifth, and sixth dimensions of the 3*N*-dimensional space; and so on". Different psychophysical facts would have different correspondence relations.

This proposal has the virtue of guaranteeing the existence of the appropriate phenomenal experiences. The problem with this proposal is that it brings along some metaphysical baggage. As I will argue below, if this proposal is true, then either mind/body dualism is true, or circumstances which we take to be logically possible turn out to be logically impossible. The metaphysical baggage of this proposal is undesirable. But without this proposal, it is simply not clear whether the appropriate phenomenal experiences would exist given the wave function ontology. Thus, the wave function ontology is an undesirable ontology for quantum mechanics.

I will now show that, if the proposal presented above is true, then either mind/body dualism is true, or circumstances which we take to be logically possible turn out to be logically impossible. Dualism, for these purposes, will be characterized as the view that mental states do not logically supervene on the physical state of the world. Assume for the moment that the psychophysical fact which specifies the correspondence between mental states and the objects in the 3*N*-dimensional world does not logically follow from the physical facts, so that there can be two worlds with the same physical facts but different psychophysical facts. Since the psychophysical facts in the two worlds are different, it can turn out that the mental states in the two worlds are different. For example, it would be easy to pick the psychophysical facts such that mental states would exist in one world but none would exist in the other.

At this point, there are two options. One is to endorse the assumption that there can be two physically identical worlds with different psychophysical facts, so that dualism is true. The other option is to reject that assumption, and retain materialism. I will first address the materialist option, then turn to dualism.

Materialism requires that mental states logically supervene on physical states, and thus that the psychophysical fact is logically necessary. The problem with materialism in this context is that it rules out as logically impossible certain circumstances that we take to be logically possible. To see this, first consider a world where the *mixed* ontology is true, and suppose that particles evolve in such a way that the x, y, and z coordinates of particle number 1 in the three-dimensional space correspond to the second, third, and fourth dimensions of the $3N$-dimensional space, and so on. Suppose further that the N particles evolve in an unusual fashion, so that no mental states exist in that world. Intuitively, such a world is logically possible. Now, consider a world like that one, except the wave function ontology is true. We take it that such a world is also logically possible. But suppose that the logically necessary psychophysical fact has the following correspondence relation: the x, y, and z coordinates of particle number 1 in the three-dimensional space correspond to the *first*, *second*, and *third* dimensions of the $3N$-dimensional space, and so on. Suppose further that it follows from this psychophysical fact that mental states exist in that world. Thus, on the materialist hypothesis, there is a possible world with the mixed ontology where mental states do not exist, but in the corresponding world with the wave function ontology mental states *do* exist. The problem here is that we take it to be logically possible for there to be a corresponding world with the wave function ontology where mental states do *not* exist. In fact, one of the intuitions that drives the whole project of the wave function ontology is that the mixed ontology is overly plentiful; it is thought that one can get rid of the three-dimensional space without affecting the predictions of quantum mechanics. Thus, the materialist option violates not only our modal intuitions, but also an intuition which drives the whole project of motivating the wave function ontology over the mixed ontology.

It is worth discussing two other ways that materialism could be true, besides the way I have considered so far. (1) Instead of there being one particular psychophysical fact which is true, it could be that *all possible* psychophysical facts are true. That is, it could be that for each possible correspondence relation between the three-dimensional space and the $3N$-dimensional space, the mental states which exist according to the psychophysical fact with that correspondence relation actually do exist. The problem with this proposal is the same as before: circumstances which we take to be logically possible turn out to be logically impossible. As before, there is a possible world with the mixed ontology where mental states do not exist, but in the corresponding world with the wave function ontology mental states *do* exist. The only difference is that, in the world with the wave function ontology, more mental states may exist than was previously thought. (2) Instead of having the psychophysical fact start with "the mental states which supervene on the state of a world where the wave function ontology is true...", it could start with "the mental states which supervene on the state of physical objects in $3N$-dimensional space...". According to this revised psychophysical fact, in the previously discussed world where the mixed ontology is true and the N particles evolve in an unusual fashion, mental states exist in that world, because they supervene on the state of physical objects in $3N$-dimensional space. Again, our modal intuitions are violated: intuitively we do not expect such a world to have mental states, and yet the materialist option entails that mental states necessarily exist in that world.

I will now turn to the dualist option for accounting for the existence of mental states in the wave function ontology. This option entails that there can exist two worlds with the same physical facts but different psychophysical facts. How bad is it for the proponent of the wave function ontology to embrace dualism? David Chalmers (1996, Chapter 4) argues that the sort of dualism where the physical world is causally closed, and consciousness naturally supervenes on the physical, but does not logically supervene, is compatible with a scientific worldview. This sort of dualism – naturalistic dualism – is the dualism which the proponent of this version of the wave function ontology would be required to embrace. Naturalistic dualism differs from interactionist dualism, where the physical world is not causally closed, and mental states have a causal influence on the physical world. Compared to interactionist dualism, it does seem that naturalistic dualism does not violate any fundamental precepts of physics. Nevertheless, I believe that one would be hard-pressed to defend an ontology for quantum mechanics which entails dualism.

There is a widely accepted attitude among contemporary researchers in foundations of quantum mechanics that one should do ‘quantum mechanics without observers’. The core idea is that one should be able to fully describe the evolution of a quantum-mechanical system without making essential reference to acts of measurements by observers on the system. More generally the idea is that quantum mechanics should not have to say special things about the nature of observers; observers should evolve according to the same dynamical equations of motion as inanimate systems. An ontology which entails mind-body dualism comes into conflict with this desideratum, however. On such an ontology, in addition to the physical state evolving in accordance with physical laws, something additional must be specified in order to account for the existence of conscious observers. Specifically, psychophysical facts must be postulated in order to determine how mental states evolve given the evolution of the physical state. Thus, dualism is a step away from the ideal of doing quantum mechanics without observers, and that is a mark against it.

In conclusion, the wave function ontology can guarantee the existence of the appropriate mental states, but only at the cost of holding either that mind/body dualism is true, or that some circumstances which we take to be logically possible turn out to be logically impossible. Otherwise, it is simply not clear whether mental states could exist given the wave function ontology. Further, everyday claims like “the cat is in the box” come out false on the wave function ontology. Because of all this, the wave function ontology is an undesirable ontology for quantum mechanics.

Acknowledgments

I thank Frank Arntzenius, Gordon Belot, Brian Kierland, Bas van Fraassen, and Jonathan Vogel for helpful discussions. I also thank an anonymous referee for helpful comments.

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Endnotes

1. One interesting aspect of these arguments is that non-relativistic quantum mechanics, the theory of quantum mechanics at issue, is often taken to be *true*, or at least potentially true. But it is well-known that quantum mechanics assumes a spacetime structure incompatible with relativity theory, and there is strong evidence for relativity theory. It is worth discussing whether there are good reasons to evaluate the potential ontologies for a theory which is known to be false, but I will not enter into that discussion in this paper.

2. According to the Ghirardi-Rimini-Weber theory (Ghirardi et. al., 1986), the wave function evolves in accordance with Schrödinger's equation (the standard dynamical equation for quantum mechanics), except when a collapse occurs on a particle. When a collapse happens on particle n, the wave function ψ changes to (following the notation of Bell 1987, 202-3):

$$\psi' (t, \mathbf{r}_1, ..., \mathbf{r}_N) = j(\mathbf{x} - \mathbf{r}_n)\ \psi(t, \mathbf{r}_1, ..., \mathbf{r}_N) / R_n(\mathbf{x}).$$

The jump factor j is a normalized Gaussian, and R_n is a renormalization factor. The value $\mathbf{x}$, representing the center of the collapsing Gaussian, is randomly chosen with probability distribution proportional to $|\psi|^2$. For each particle, a collapse randomly happens at a rate of $1/\tau$, where τ is a new fundamental constant, taken to be 10^{15} seconds.

3. According to Bohm's (1952) interpretation, the wave function $\psi(t, \mathbf{x}_1, ..., \mathbf{x}_N)$ always evolves in accordance with Schrödinger's equation. On one version of Bohm's interpretation, it is described as postulating N point particles evolving in three-dimensional space. On this version, each particle always has a definite position $\mathbf{r}(t)$. The position of a particle k evolves in accordance with the velocity equation:

$$\mathrm{d}\mathbf{r}_k/\mathrm{d}t = \nabla_k S(t, \mathbf{r}_1, ..., \mathbf{r}_N)/m_k .$$

The S function comes from the following decomposition of the wave function:

$$\psi(t, \mathbf{x}_1, ..., \mathbf{x}_N) = R(t, \mathbf{x}_1, ..., \mathbf{x}_N) \exp[iS(t, \mathbf{x}_1, ..., \mathbf{x}_N)/\hbar] .$$

Alternatively, Bohm's interpretation can be described as postulating one *universal particle* evolving in $3N$-dimensional space; this particle gives the configuration-space representation of the positions of the N particles in three-dimensional space.

4. My arguments can also be taken to show that the analogous ontology for classical mechanics – that of a universal particle evolving in a $3N$-dimensional space, and no three-dimensional space – is an undesirable ontology. The reason I focus on quantum mechanics is two-fold. First, the $3N$-dimensional ontology is not considered to be a live option for the correct ontology for classical mechanics. In contrast, Albert has trenchantly defended the wave function ontology for quantum

mechanics in print, John Bell (according to Albert) is another proponent, and I have heard it advocated in discussion with other philosophers (mostly promulgators of Bohm's interpretation). Second, there is prima facie a good reason to believe in the wave function ontology for quantum mechanics: the wave function is a fundamental part of quantum mechanics, and the wave function of the universe cannot be represented as evolving in three-dimensional space.

5. According to Ghirardi et. al. 1995, the mass distribution $\mathtt{M}_i$ is defined in terms of the wave function by

$$\mathtt{M}_i = \langle \Psi | M_i | \Psi \rangle,$$

where it is assumed for simplicity that three-dimensional space is divided into discrete cells i, and where M_i is the mass operator for cell i. This mass is "accessible" (following the terminology of Bassi and Ghirardi 1999) just in case $\mathtt{R}_i \equiv \mathtt{V}_i/\mathtt{M}_i^2 \ll 1$, where the variance $\mathtt{V}_i$ is defined as

$$\mathtt{V}_i = \langle \Psi | (M_i - \langle \Psi | M_i | \Psi \rangle)^2 | \Psi \rangle.$$

6. Here and elsewhere, the word "respectively" is implicit.

7. In fact, given the evolution of objects in a $3N$-dimensional space, it is not determined whether that represents the evolution of N hypothetical particles in a three-dimensional space, or $3N/2$ hypothetical particles in a two-dimensional space (assuming $3N$ is even), and so on.

8. The predictions about phenomenal experiences would be made by the physical theory in conjunction with ancillary hypotheses about how phenomenal experiences are related to physical states.