The Non-Equivalence of Empirically Equivalent Theories: The Case of Hidden Variables in Quantum Mechanics

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1 Introduction

The problem of empirical underdetermination and theoretical equivalence is: given two theories that give the same predictions for empirical phenomena, how are we to choose one of the two as being the correct theory? In this paper, I will take as a case study, the issue of choosing between standard quantum

mechanics (also known as the Copenhagen interpretation due to Neils Bohr and Werner Heisenberg; hereafter **OQM** for orthodox quantum mechanics) and David Bohm's hidden variables theory of quantum mechanics (hereafter **BQM**). There are positivistic formulations of empirical equivalence that insist that theories such as this pair are fully equivalent. I will reject such a notion and suggest that it only holds for a particular version of empirical equivalence due to Reichenbach (that I will term R-equivalence); the crucial notion in theory choice is explanation. I will depict the Einstein-Podolsky-Rosen (**EPR**) argument as a suggestion for the construction of an empirically equivalent (at minimum) theory to **OQM**. In conclusion, I will argue that the thesis of notational variance for empirical equivalence fails for the case at hand and that the theories are not equivalent while being empirically equivalent.

2 Hidden Variable Theories

If a hidden-variable theory T^* is a theory empirically equivalent to some previously existing theory T, we can ask the following:
1. Are the two theories equivalent? (More generally, when are two theories equivalent?)
2. Given a definition of empirical equivalence, are two empirically equivalent theories equivalent as well?

If the two are equivalent then on what grounds can we select one over the other? Is there anything philosophically wrong with hidden variables? Must a theory have empirical payoff and make new predictions to be counted as a contender to a previously successful theory? Are there other (non-evidential) criteria for scientific theories besides empirical adequacy? If a hidden variable theory can be formulated that explains experimental results better than non-hidden variable theories then is it only Occam's razor that prevents us from accepting it? Is ontological parsimony all there is to choosing amongst theories? Is a hidden variable theory 'just metaphysics'?

Consider the following definition of hidden variable theories[1]:

[1] Jammer, Max. *The Philosophy of Quantum Mechanics*, Wiley and Sons, New York, 1974, page 256

> In a given theory T about certain physical systems S certain variables v describe the states of S; in a theory $T^{'}$ about S certain variables $v^{'}$ (which may be dynamical quantities or other hypothetical entities) which are not experimentally detectable within the framework of T describe the states of S; if the values of v, or of explicitly defined functions or functionals associated with v as used in the state description in T can be obtained by some averaging operation over the values of $v^{'}, v^{'}$ are called hidden variables (with respect to T) and $T^{'}$ is called a hidden variable (or interpretation) with respect to T.

Hidden variables are, by definition, unobservable and experimentally undetectable. If so, why introduce a hidden variable theory? Physics is used to positing new unobservables when experimental data warrants it; witness the postulation of the existence of the neutrino by Pauli to save the conservation of energy and momentum laws. Why posit the existence of experimentally undetectable entities, though, when a empirically adequate theory is available? The motivations are likely to be non-evidential criteria[2]:

> Note that even if we accept (as empirically adequate) an inherently probabilistic theory T, we do not therefore have to deny the thesis of determinism. The theory could be true but incomplete: by proper *supplementation* [my emphasis] it might be made into a determinist theory T^*.

Here the desire to restore a certain philosophical doctrine, determinism, is at play. I will argue that choice between theories is based on more than just empirical equivalence: it often is a matter of which philosophical doctrines or methodological frameworks we hold most important and worth conserving.

2.1 Empirical Equivalence and Reichenbach Equivalence

A definition of empirical equivalence is required. One pair of definitions is the positivist view (based on the verificationist theory of meaning) and the probabilistic conception of equivalence as discussed by Reichenbach[3]. The verificationist definition runs as follows:

> **V:** Two theories are fully equivalent despite any apparent differences if and only if they have the same verification conditions: a theory is equivalent to the set of observation conditionals that follow from the theory.

If two theories have the same verification conditions, then, they carry the same *meaning* and have the same *content*. This is a strong method of handling the problem of

[2]Hughes, R.I.G, *The Structure and Interpretation of Quantum Theory*, Harvard University Press, Cambridge, 1989, page 109

[3]Reichenbach, Hans, *The Rise of Scientific Philosophy*, Berkeley, University of California Press, 1968, Chapter 8 and *Experience and Prediction*

theoretical equivalence since it avoids problems with theory choice; Reichenbach contends the option is a conventional one (I'll call this view R-conventionalism). The positivist definition can be used to construct a possibly anti-realist position: that the content of a theory is its observational terms and no more.

This account is ambiguous (and too impoverished as an account of scientific theory adoption; more on this below) for several reasons: firstly, we might accumulate additional evidence that actually causes us to *undo* the verification we had carried out earlier, rendering equivalence to be a particularly *unstable* notion. The verificationist could contend that two theories are equivalent if and only if, in all possible circumstances, they are verified to precisely the same degree. This does us no good, since we are left with the vagueness of 'all possible circumstances'. Should this be physical possibility or logical possibility? Reichenbach appears to think that this should be physical possibility. There is scope for disagreement: a possible alternative construal is 'possible according to the theory in question'. What one theory might construe as 'possible circumstances' might be different from the other theory.

Reichenbach's probabilistic conception can be defined in two distinct ways on different readings. One version is as follows[4] :

> T_1 is empirically equivalent to T_2 if and only if for any possible observation sentences $O_1, O_2, \ldots, O_{m+1}, \ldots, O_n$:
> $Prob(O_1 \wedge O_m | T_1 \wedge O_{m+1} \wedge \ldots O_n) = Prob((O_1 \wedge \ldots O_m | T_2 \wedge O_{m+1} \wedge \ldots O_n)$

The above formulation states that two theories are empirically equivalent if and only if the probabilities of future observations given by the two theories are the same (given the same set of prior observations). Empirically equivalent theories in this formulation inherit each others inductive weight as well.

Another version is as follows[5]:

> T_1 is R-equivalent to T_2 if and only if for any possible observation sentences $O_1, O_2, \ldots, O_{m+1}, ...O_n$:
> $Prob(T_1 | O_1 \wedge \ldots O_2 \ldots \wedge O_m) = Prob(T_2 | O_1 \wedge O_2 \wedge \ldots O_n)$

In the above, two theories are R-equivalent, if the conditional probabilities of the two theories given the same set of observations is equal i.e those theories are R-equivalent that are made equally probable by the same set of observations.

The probabilistic conceptions of theoretical equivalence aren't problem-free. What happens if some observations predicted by a theory do not occur with the frequency predicted by a theory[6]? Would we say that we had confirmed a theory but just lowered its probability? This seems counter-intuitive; it seems more natural to say

[4] This formulation is due to Hartry Field

[5] This formulation is due to Hartry Field

[6] Given a standard statistical definition of probability $P(A) = \#$ of favorable cases/Total $\#$ of cases

we *disconfirmed* the theory. Moreover, given the definition of probability for pairs of theories, the disjunction of a pair of theories will land up having a higher probability than either of the two theories. That is, given $P(T)$ and $P(T^*)$, where $0 \leq P(T) \leq 1$ and $0 \leq P(T^*) \leq 1$, $P(T \vee T^*) = P(T) + P(T*) \geq P(T), P(T^*)$.

R-equivalence as defined above implies empirical equivalence with no caveats thrown in. If the observations that the theory predicts make the theories equally probable, then the two theories will be empirically equivalent as well. Now, the notion of observations making a theory just more probable should be more than just a mathematical construct. A theory should be made more probable by the observation sentences if it provides a better *explanation* of the observation sentences. The important point is that equivalence doesn't go the other way unconditionally above; that is, if T_1 and T_2 are empirically equivalent, then they are R-equivalent if and only if $P(T_1) = P(T_2)$[7]. However, $P(T_1)$ and $P(T_2)$ are vague; it's not clear what it means to talk of the *probability of a theory*. Surely, the probability of a theory is just its likelihood of being *correct*. What being correct amounts to, is of course, what theory choice is all about.

In any case, it seems wrong to say that two theories are equivalent if they give rise to the same predictions; what if one theory gives a *better account* of them? Shouldn't those observations make the theory more probable that gives a better explanation of them? The probability of a theory, or, the relative probability of a theory as compared to another, though, (this is a point that applies to all the definitions given above) is most coherently be based on factors such as simplicity, initial plausibility and supposed extendibility of prediction. Crucially[8]:

> The notion of confirmation or positive support involves far more than the mere absence of falsification. The mere fact that a hypothesis has not been falsified does not in itself indicate that the hypothesis has received the slightest confirmation.

The definition of empirical equivalence, then, is merely the first step in admitting a theory to the tribunal of theory choice. It is a bare minimum to be met and is no indication that the theory is the best explanation of the phenomena in question. This suggests that if an alternative theory, empirically equivalent and more explanatorily powerful, can be constructed, it should be and deserves to be counted as the correct one.

If, after having established that the two theories are empirically equivalent, we try and establish R-equivalence, we are then making a choice of theories. *The act of determining whether two theories are R-equivalent, is the process of trying to make a choice between the two of them; establishing empirical equivalence being merely the first step in this process.* If the two theories turn out to be R-equivalent (that is, we

[7] This, as I argue below, doesn't hold in the case of **OQM** and **BQM**.

[8] Audi, Michael. *The Interpretation of Quantum Mechanics*, University of Chicago Press, Chicago, 1973, page 79

find them to be equally probable in being equally explanatory, descriptively simple and so on) as well, then the two can be termed fully equivalent. If we can establish that the two theories are not R-equivalent, then they aren't equivalent, period. If two theories are R-equivalent, then no choice can be made (other than some forced choice such as R-conventionalism) pending empirical support that forces us to go one way or the other.

The dismissal, then, of hidden variable theories because they have 'no empirical payoff' or as 'mere metaphysics', misses the point. Granting the status of empirical equivalence to a hidden variable theory *requires no concessions*; we were *forced* to look for an alternative theory when our current theory gave us dissatisfying explanations. A hidden variable theory creates a problem of theory choice *only* when it offers a better explanation of the phenomena than the current theory. What do the two theories under consideration say anyway? Why would one say that there is a problem with the accepted theory? Why is there a conflict between the two? Most importantly, why are the two theories *not* R-equivalent?

3 OQM

While the actual statements of the quantum mechanical formalism are fairly complex, one can summarize them fairly succintly without too much loss of precision [9]. **OQM** makes the following claims about quantum mechanical systems:

1. The wave function or state vector ψ is a *complete* or *maximal* specification of a quantum mechanical system. No more information is available or forthcoming. All there is to the physical state of the system is captured in this specification. Identical wave functions or state vectors for two systems imply identity of the systems. Measurable properties are termed *observables* and are represented by linear operators on the vector spaces associated with the state vectors of the given system. The relationship between the observables and the state vector is as follows[10]:

> If the vector associated with some particular physical state happens to be an eigenvector, with eigenvalue (say) a, of an operator associated with some particular measurable property of the system in question (in such circumstances, the state is said to be an eigenstate of the property in question), then that state has the value a of that particular measurable property.

[9] Descriptions of the Von Neumann formalism are presented in numerous sources on the subject. The description I have presented here is due to the following sources: Albert, David. *Quantum Mechanics and Experience*, Harvard University Press, Cambridge, 1992. Chapter 2. Maudlin, Tim. *Quantum Non-Locality and Special Relativity: Metaphysical Intimations of Modern Physics.* Oxford: Basil Blackwell, 1994, Chapter 4

[10] Albert, David. *Quantum Mechanics and Experience*, Harvard University Press, Cambridge, page 31

2. The wave function always evolves in accord with the general Schodringer equation as follows (H is the Hamiltonian or energy operator for the system):

$$\frac{\delta\psi}{\delta t} = -iH\psi$$

3. If two operators A and B on the space defined above do not commute, that is, if $AB \neq BA$, then the two quantities represented by those operators are *conjugates* of each other and precise knowledge of one rules out *any* knowledge of the other. This is the basis of the Heisenberg Uncertainty principle. When we measure the value of one of the two conjugate operators above, there is no *fact of the matter* as to what value its partner had. This is not just some simplistic disturbance model of measurement; this is a fundamental constraint on what claims we can make about the intrinsic properties of objects. The two conjugate operators above represent two possible attributes that it is possible to determine about an object but we can make no statements about them having any 'real' status *simultaneously.* If we measure the position of a particle using position measuring apparatus, there is no sensible statement that can be made about its momentum and the same holds true for position if we decide to measure the momentum instead.

4. There is a fundamental *discontinuity* in the description of systems according to the Copenhagen interpretation. Systems behave in one fashion when not being measured and in another when undergoing measurements. These rules, the genesis of *the measurement problem* can be stated as follows[11]:

> I. When no measurements are going on, the states of all dynamical systems invariably evolve in accordance with the dynamical equations of motion.
> II. When there are measurements going on, the states of the measured system evolve in accordance with the postulate of collapse, not in accordance with the dynamical equations of motion

5. While the Schodringer equation is deterministic in its evolution, the set of values that may be obtained from it is governed by a probability distribution; which one of the values gets selected is decided at the time of measurement. Before the measurement there simply is no fact of the matter as to what value the observable had. The 'postulate of collapse' runs thus: when we carry out a measurement of an observable O, the state vector 'jumps' into an eigenstate of the operator. The wave function[12] 'collapses' to a particular value at the point of measurement. All of this is dependent on what constitutes a measurement; something for which there is no precise definition forthcoming.

6. According to the *superposition principle*, any system is in a superposition of *all possible physical values before measurement is carried out on the system.* The

[11] Albert, David. *Quantum Mechanics and Experience*, Harvard University Press, Cambridge, page 80

[12] In the original probabilistic interpretation due to Max Born the wave function was interpreted as a probability wave, the graph of which represented the set of all possible values.

momentum of a particle (if measured) goes from being in a superposition of all possible values to one definite value at the time of measurement. This does violence to our notions of what constitute intrinsic properties or states of affairs. How or why the wave function collapses from a superposition of all possible values to one value is not clear; such a question, in this framework, is not proper. The only use of classical concepts in this entire treatment is to facilitate discourse about these measurements.

7. The complete dynamics of the system is *probabilistic* rather than deterministic. This is an intrinsic, not epistemic constraint. Given a particular configuration at time t, the probability for a particular wave function at some point t^1 is given by the square of the amplitude of the wave function: $\mid \psi(t^1) \mid^2$. Systems that are isolated from one another might start out as being identical and over time, slowly evolve into radically different states. This probabilistic element is part of the collapse of the wave function.

With the special status accorded to measurement, this formulation of quantum mechanics is highly subjective; physical quantities don't exist until they are measured. The Copenhagen interpretation forbids the assignment of intrinsic properties to physical systems; we speak of them only with reference to the measuring apparatus used to measure them. There is a radical, sharp, division of the world into two different domains, with the split taking place at the time of the wave collapse. Bell sums it up [13]:

> To know the quantum mechanical state of a system implies, in general, only statistical restrictions on the results of measurements.

4 The EPR argument: a suggestion for an empirically equivalent theory

The original[14] (**EPR**) paper is plausibly viewed as the original proposal for hidden variables in quantum mechanics. **EPR** make a distinction between objective reality which is *independent* of any theory and the physical concepts with which the theory operates. These concepts are intended to correspond to or with objective reality; we picture reality by means of these concepts. The success of a theory is to be judged according to the following two conditions:

1. Is the theory correct?
2. Is the *description* given by the theory *complete*?

I take it that (1) above simply means that the theory be empirically adequate as

[13] Bell, John. "On the problem of hidden variables in quantum mechanics", *Speakable and Unspeakable in Quantum Mechanics*, Cambridge University Press, Cambridge, 1987, page 1

[14] Einstein, Albert, Podolsky, Nathan, Rosen "Can Quantum-Mechanical Description of Reality be Considered Complete?", *Quantum Theory of Measurement*, (Wheeler and Zurek eds.), Princeton Press, 1983.

indeed **EPR** do; that is, the theory not be *falsified* by the data. **EPR**'s definition of completeness is more interesting[15]:

> Every element in the physical reality must have a counterpart in the physical theory

I take this to be the part that **OQM** lacks and which hidden variables fulfill; **OQM** makes only epistemic claims, there is no *realist* interpretation of it possible. As we will see, hidden variables will "fill" out **OQM**, provide sufficient elements in the theory to match their physical counterparts and make it possible for ontological claims to be associated with the theory. **EPR** also offer the following definition of a sufficient condition of reality[16]:

> If without disturbing the system, we can predict with certainty the value of a physical quantity then there exists an element of physical reality corresponding to that physical quantity.

This particular criterion suggests that the debate about the completeness of quantum mechanics is a clash between the instrumentalism and associated anti-realism of **OQM** and the realist view of **EPR**. Put in this light, the debate between **BQM** and **OQM** acquires a different look.

The **EPR** argument relies upon the quantum mechanical formalism; if two operators A and B corresponding to physical observables do not commute, then precise knowledge of one precludes knowledge of the other. So for **EPR** either:

a) The quantum mechanical description by means of the wave function does not give a complete description.
Or:
b) When operators corresponding to two physical quantities do not commute then the two quantities cannot have simultaneous reality.

An analysis of the formalism for composite systems (systems specified by joint wave functions) possessing observables (A, B) and (P, Q) respectively reveals that by our choice of measuring A or B on the first system, we can determine P or Q on the second system without disturbing it where P and Q are two noncommuting operators[17] (it is presumed that two systems are prepared in a joint state and then separated; however, it is a consequence of the formalism that the systems remain in an *entangled* state). Since it must be presumed that both of these properties had existed all along and therefore had simultaneous reality (or we have action-at-a-distance, violating locality and requiring a preferred frame for action), we are caught in a contradiction. The only alternative would be to deny that P and Q existed until measured; a concession to a mind-dependent, subjective reality that **EPR** clearly feel

[15] Ibid., page 138
[16] Ibid., page 138
[17] Ibid., page 139

to be intolerable. **EPR** suggest that these measurement results obtained at separated locations are determined in advance by means of dynamical variables correlating the states of the system after separation. These dynamical variables are the so-called hidden variables. **OQM** stands indicted of incompleteness by **EPR**; a new theory is needed.

It's clear that **EPR** are recommending the construction of a theory empirically equivalent to **OQM**: as a replacement and not just as an interestingly equivalent theory. They agree that **OQM** does a fine job of making predictions; *what it lacks is a an explanatory mechanism or structure with which to correlate parts of the theory with the phenomena*. The theory requires 'filling out'. **EPR** would certainly demand that any competitor theory for **OQM** should *at the least* give us the same success with respect to the phenomena. To expect any less would just be self- defeating.

5 Bohm's Hidden Variables Theory

How is **BQM** empirically equivalent to (and a problem for) the orthodox formulation? How does it take care of the **EPR** problem? Bohm defines hidden variables as follows[18]:

> ..a further set of variables, describing the state of new kinds of entities existing in a deeper subquantum mechanical level and obeying qualitatively new types of individual laws

We might describe **BQM** as follows:

1. The wave function is not a maximal specification (or a specification at all) of a quantum mechanical system; it plays the part of a force field that guides a particle's possible positions. In addition to the wave function, a system possesses other physical properties. Particles always have definite positions. This means that systems can have definite observable properties even when they are not in eigenstates of the associated operators; a particle can have a position even if its wave function is not an eigenstate of the position operator. Even if two systems have the same wave function, they might be in different physical states since their other physical properties can differ. The extra physical parameters in **BQM** system are the hidden variables.

2. The wave function is always described in accord with Schodringer's equation: there is no need for the infamous collapse. The primary physical property of this wave function is its amplitude at every point in space.

3. The overall dynamics (the evolution of the wave function) of a **BQM** system is *always* deterministic; given the positions of particles in a system and the complete

[18]Bohm, David. "A suggested interpretation of the quantum theory in terms of hidden variables", *Quantum Theory and Measurement*, Wheeler and Zurek eds., Princeton University Press, 1983, page 372

wave function, the positions of all particles at any future point in time can be calculated. In addition to the Schodringer equation, we have an equation that provides a deterministic law for the motion of particles:

$$\frac{\delta X_i(t)}{\delta t} = \frac{j_i(X_1 ... X_{3N}, t}{|\psi(X_1 ... X_{3N}, t)|^2}$$

This equation gives the rate of change of the particle positions (the X terms); any shortcomings in our calculations are *epistemic constraints* and not irreducible indeterminism as in **OQM**.

How does **BQM** give the same probabilities for its observations if it is a deterministic system and **OQM** is stochastic? Simple. A deterministic theory can only make non- probabilistic predictions if one has perfect knowledge of the system's initial conditions. If such perfect knowledge is not available, a probability function defined over the possible initial states *evolves deterministically* into a probability function over possible final states. Such initial uncertainty exists in quantum mechanical systems[19], is proportional to ψ^2, the square of the wave function, and arises because of the lack of precise knowledge of the initial co- ordinates of the observed system and apparatus: this is an epistemic notion. If a probability function $\mid \psi(0) \mid^2$ is the description of the initial configuration, then by the Schodringer equation, the probability of a later configuration at time t will be given by $\mid \psi(t) \mid^2$. These probability distributions are of course, exactly those predictions that are afforded to us by **OQM**.

The wave function does a great deal of work; **BQM** uses the wave function which is located at every point in space to do away with the need for the superposition principle. It is a field just as real as any electromagnetic field in Maxwellian theory. Superposition now stands *explained*; it is the wave function that "splits up" to take all possible paths in a position measuring experiment while the particle itself just takes one since it had a definite position all along. It is the wave function that makes the particle position sensitive to experimental conditions by 'informing' it of apparatus settings. The real hidden variable is the wave function. I had characterized "other physical parameters" as hidden variables above. These parameters are reflected in the wave function. It is the addition of particle positions to the standard picture and treating all measurements as being about particle positions that renders the wavefunction a hidden variable. What are the explanatory advantages that **BQM** provides and what are some possible objections to it?

[19] Just as in classical statistical mechanics.

6 For and Against BQM

6.1 Impossibility Proofs

Ironically, John Bell makes the strongest case for **BQM**[20]; the Bell's theorem only proves that *local* hidden variable theories cannot explain quantum mechanical phenomena. The other decisive evidence against hidden variable theories, the so-called "impossibility" proofs due to Von Neumann[21], Gleason[22], Jauch and Piron[23], have been shown by Bell [24] to *only hold* in the case of a certain specialized class of hidden variable theories i.e local, non-contextual theories. An observed value is contextual if the microsystem corresponding to that observable has its behavior partially determined by the environment; **BQM** is both non-local and contextual and thus, immune to the impossibility proofs.

6.2 The Restoration of Determinism, Objectivity and Some Other Virtues

Importantly, for Bell, the deterministic picture of nature is restored by hidden variable theories. Randomness and irreducible stochasticity are often epistemic constraints; who is to say that is not the case here?[25]:

> Are quantum mechanical states averages over better defined states for which individually the results would be quite determined? These are the so-called dispersion free states which are specified not just by the quantum mechanical state vector but by additional hidden variables.

As noted above, the **OQM** description is highly subjective. This is done by means of the quantum mechanical state function which characterizes the classical conditioning of quantum mechanical systems and permits predictions about subsequent events at the classical level: the theory is *about* measurements and *requires* an observer responsible for making measurements. Bell pictures this description of the world according to **OQM** as follows[26]:

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[20] This is a theme that is present in a large number of essays in *Speakable and Unspeakable in Quantum Mechanics*. I have only touched upon his views briefly.

[21] Neumann, Jon Von. *The Mathematical Foundations of Quantum Mechanics*, Princeton University Press, 1952. As cited by Bell above.

[22] Gleason, *A.M. J. Math* & Mech. 6, 885 (1957). As cited by John Bell above.

[23] Jauch, J.M and Piron, *C. Helv. Phys. Acta. 36*, 827 (1963). As cited by John Bell above.

[24] Bell, John. "On the problem of hidden variables in quantum mechanics", *Speakable and Unspeakable in Quantum Mechanics*, pages 1-13

[25] Bell, John. "On the problem of hidden variables in quantum mechanics", *Speakable and Unspeakable in Quantum Mechanics*, page 1

[26] Bell, John. "Introduction to the hidden variable question", *Speakable and Unspeakable in Quantum Mechanics*, page 28

$$(C_1, C_2, C_3, \ldots \psi)$$

where C_1, C_2 etc. are classical variables and ψ is the quantum mechanical state function. What is unclear about this picture is the location of the *boundary* between the classical and quantum mechanical domain. The existence of such a boundary, located right where the collapse of the wave function occurs and where **OQM** loses coherence, indicates that we are in the presence of a theory that is of "manifestly approximate character"[27].

This desire for objectivity is perhaps indication of another motivation; a desire to have an account that has no discontinuities[28]:

> The possibility of a homogenous account of the world which is for me the chief motivation of the study of the hidden variables possibility.

In addition, part of the irreducibly stochastic nature of **OQM** could be done away with since the apparently random fluctuations are determined by the extra hidden variables

Might there be empirical grounds for choosing a hidden variable theory? The hidden variable theory could be one way of explaining quantum correlations observed in polarization experiments that violate Bell's inequality[29]:

> This would strongly suggest that the outcomes of such measurements along arbitrary directions, are actually determined in advance by variables over which we have no control but which are sufficiently revealed by the first measurements so that we can anticipate the result of the second. There then need be no temptation to regard the performance of one measurement as exerting any causal influence on the second distant measurements. The description could then be made local. This enables us to derive a picture of a system that is evolving continuously and locally in ordinary space and time.

Unfortunately, we cannot claim this as a virtue of the hidden variable theory in question since as Bell's theorem shows, no local theory can reproduce quantum mechanical predictions.

There are other ways in which a hidden variable theory is instructive. A particle need not spin, though all the experimental phenomena associated with spin can be reproduced. This frees us from the task of having to impose our notions of what "spinning bodies" look like on particles (the problem of having to talk about the degrees of freedom that a spinning body possesses disappears). Rather than talk electrons being tiny spinning spheres we talk about a set of 2 discrete values that

[27] Ibid., page 29
[28] Ibid., page 30
[29] Ibid., page 30

an electron's position can possess after a "spin measuring experiment". Importantly, even if the boundary that we observed above remains and just becomes more sharply defined, some classical variables will become indispensable, doing away with the need to throw out all classical concepts. The quantum and classical levels may be seen to be interacting in continuous fashion rather than in the radically discontinuous fashion as envisaged by **OQM**; classical variables may be pictured as being continuously influenced by a quantum mechanical state.

6.3 Is BQM Ad-Hoc?

Is **BQM** ad-hoc and parasitic on the original formulation? Consider Einstein on the subject[30]:

> Have you noticed that Bohm believes that he is able to interpret the quantum theory in deterministic terms? That way seems too cheap to me..

Charges of ad-hocness are easily dismissed though; there are analogies (and not just formal ones) between Bohm's equations and classical Hamilton-Jacobi equations. Furthermore, Bohm's theory provides a fairly well defined dividing line from Newtonian mechanics[31]. The lack of empirical payoff is not a serious issue: empirical equivalence is only the first step in helping us come to a choice of theories[32]. Is the hidden variable theory an exact repetition in another language? Does it say nothing that the Copenhagen interpretation hadn't already said[33]? Not so. There is a real difference in the ontologies and a recasting of the mechanism of measurement[34].

6.4 Non-Locality

Non-locality is hardly an embarrassment for **BQM** since Bell's theorem shows that no local theory can reproduce predictions for quantum mechanical phenomena[35]: non-locality is a necessary feature of any theory that duplicates quantum mechanical predictions. **OQM** is non-local as well; witness the instantaneous collapse *over all space points* of the wave function. What *is* a problem about non-locality is that it appears to require a dismissal of another (extremely) valuable scientific theory; the Special Theory of Relativity. The only way to get out of that dilemma is to interpret

[30] As cited by John Bell in "Einstein-Podolsky-Rosen Experiments" in *Speakable and Unspeakable in Quantum Mechanics* above.

[31] These points are due to Tim Maudlin in *Quantum Non-Locality and Special Relativity.*

[32] Strictly speaking, there are experiments, designed by Bohm and Hiley that could confirm which theory is the correct one. See David Bohm and BJ Hiley *The Undivided Universe: An Ontological Interpretation of Quantum Theory*, Routledge, 1992

[33] Heisenberg, Werner. As cited by Audi in *The Interpretation of Quantum Mechanics*, page 76.

[34] More on this issue in the section on notational variance below

[35] Bell, John. "A theory of local beables", *Speakable and Unspeakable in Quantum Mechanics.*

the special theory of relativity as an operational theory, that is, one that tells us about whether we can detect preferred frames or not rather than as a objective theory of space-time. Significantly, measurement statistics for **EPR**-type experiments are unaffected by the order of measurement, rendering impossible the use of entangled states to send a superluminal signal and violate Lorentz invariance[36].

6.5 Ontological Profligacy

The mere positing of extra unobservable entities is no reason to reject the hidden variable theory. The first theories of atomism were the first hidden variables theories; no one would suggest that they were misguided. A sparse ontology does us no good if it forces absurd interpretations or physical laws; ontological parsimony is a desirable feature but Occam's razor is not to be used indiscriminately. **BQM** takes its primary responsibility to be the explanation of physical phenomena; the ontology to be adopted is the one that best explains the phenomena. An ontology where wave functions are physical entities in configuration space is to be preferred to one that has *no* ontology.

7 Issues in Theory Choice

7.1 Conventionalism

When confronted with an empirically equivalent pair of theories, R-conventionalism entails that theory choice be a a matter of convention; 'shaking hands' on an agreed upon choice. Some statements in a theory are regarded as being true or false as a result of convention and this rules the other theory to be *a priori* false. But, conventionalism comes into play when we have established that the two theories are R-equivalent. Only then do we have nothing else to go on to make a choice and we adopt one as the framework within which to do further scientific work[37].

In circumstances other than the choice between R-equivalent theories, R-conventionalism is a misleading label, suggesting as it does, some manner of arbitrary choice. There is nothing arbitrary in the choice of one theory over another if they are not R-equivalent. Arbitrariness would seem to suggest that we could just as well toss a coin and just pick a theory over another. In this case, that's not possible; the two theories in question provide us with different grounds for wanting to believe in them.

[36] The putative clash of quantum mechanics and special relativity is an issue explored by Tim Maudlin in *Quantum Non-Locality and Special Relativity.*

[37] A so called 'conventional' choice could also be conventional in another sense of the word; it enables us to follow conventions that we have followed before. A conventional choice like that would seem to reflect all our biases of induction and preferences for a particular world-view. I might stand guilty of conflating this with inductive biases though.

7.2 Simplicity and Initial Plausibility

While not intending to conflate the two concepts here, I suggest the two are linked and that application of one of these concepts to a pair of competing theories involves the other as well. It might be argued too, that most considerations of simplicity and initial plausibility are made on inductive grounds. Initially plausible theories are often more simple; conversely, the simplest theories tend to carry the highest degree of initial plausibility. These come apart in the case of quantum mechanics. While **OQM** has descriptive compactness in its axiomatization and carries great plausibility as a result of its unprecedented empirical success, it lacks simplicity in its interpretation. The fact that the wave function performs so many tasks in **BQM** and has been promoted to physical entity status might strike one as being implausible. But, *something or the other formerly held to be plausible* is going to be done away with in order to understand the phenomena that we are faced with[38]. In the quantum mechanics debate, it is tempting to characterize the idea of what constitutes simplicity and complexity as being up for grabs. **BQM** carries greater plausibility, I suggest since the losses it entails for a classical world-view are fewer.

On standard construals of simplicity, it's hard to imagine ruling that **OQM** is simpler than **BQM**. Superpositions and collapses of mathematical entities do not a simple theory make. At the same time, there isn't a conceptual or analytic interconnection between notions of simplicity and degree of empirical support. **OQM** fails to possess simplicity while retaining an instantaneous, non-local, unexplained, "collapse" of a mathematical entity that causes the values of microscopic observables to change. **BQM** however, suffers from a lack of initial plausibility because of its non-relativistic nature[39] and its lack of causal symmetry between wave functions and particles (wave functions affect particles, particles don't affect wave functions).

7.3 Skepticism about scientific realism

A strong case for a particular kind of skepticism about scientific realism that arises in theory choice comes from the verificationist theory and is the basis for the notational variance argument. For this position, there is full underdetermination of our ontologies; given a scientific theory T, we can always reformulate a "scientifically indifferent variant", T^* positing distinct entities. The ontology we attribute to the world then will depend on an apparently conventional choice (or based on factors such as simplicity etc.) between T and T^*. Such theory pairs are notational variants of another or different entities in the two theories have been promoted or relegated to mathematical or physical entity status in the other theory.

[38] I have not included in this paper, any descriptions of experiments that are regarded as classical cases of quantum mechanical "strangeness" such as double slit experiments, the Davisson-Germer experiment(electron interference) and the Stern- Gerlach experiments (particle behavior in non-uniform magnetic fields.

[39] A version of **BQM** for relativistic quantum field theory was worked out and presented by Bohm and Hiley in *The Undivided Universe.*

The pair of theories that we are considering are clearly, though, *not* notational variants of one another. If this wasn't already clear in the theory statements presented a few pages ago, consider John Bell on **BQM**[40]:

> No one can understand this theory unless he is willing to think of as a real objective field rather than just a probability amplitude. Even though it propagates not in 3-space but in $3N$-space.

The wave function is reinterpreted in **BQM** and introduces new members to the ontological realm that have no counterpart in **OQM**. It includes forces that are ignored in the orthodox theory. In addition to forces acting on particles due to classical potentials, particles are also subject to the so-called quantum-mechanical potential. Generally, equations of motion are obtained by assuming the negligibility of a ψ term that is proportional to the square of the ubiquitous Planck constant, h. Bohm suggests that this be retained and interpreted as a potential. The Schodringer equation can then be re- interpreted as quasi-classical equation that uniquely and exactly describes the paths of individual particles. The source of this potential is a field whose strength is related to the amplitude of Schodringer wave equations. So while the wave function is 'merely reintepreted', its reinterpretation introduces new physical factors in our calculations and renders as more credible, its explanatory mechanism.

8 Conclusion

BQM and **OQM** are not equivalent though they are empirically equivalent. The decision of having to choose between them illustrates the fact that the factors that we actually use to make a choice of theories constitutes the *real empirical support*, since it is not founded on any *a priori* considerations. The use of the word *a priori* is misleading; its use implies that we have some intuition given to us independently of experience that makes us choose one theory over another. This is simply not the case; all our intuitions of theory choice arise on inductive grounds.

The straightforward lesson to be learnt from the quantum mechanics case is that a good theory besides being empirically successful, must have proper explanatory power and sufficient interpretive value. Our characterization of a theories adequacy is also based on inductive evidence of certain concepts having worked in the past. The **OQM** picture is curious: our faith in theories that have worked in the past (since sub-atomic particles as fundamental entities work well) leads us to characterize it as being adequate in one sense and inadequate in another (since one classical concept or the other goes out the window).

I hope the the discussion above has established that there are no philosophical barriers to constructing an empirically equivalent theory that is intended to replace a

[40] Bell, John. "Quantum Mechanics for Cosmologists", *Speakable and Unspeakable in Quantum Mechanics*, page 128.

previously successful theory; the problem of underdetermination of physical theories is not so severe so as to prevent us from coming to a decision in most matters. Bell puts it well[41]:

> ..vagueness, subjectivity, and indeterminism are not forced upon us by experimental facts but by deliberate theoretical choice..

The proper choice of theories acquires even greater importance in the case of the most fundamental theory available to us.

[41] Bell, John. "On the impossible pilot wave", *Speakable and Unspeakable in Quantum Mechanics*, page 160