

# Explaining the *Unobserved*—Why Quantum Mechanics Ain't Only About Information

Amit Hagar\*      Meir Hemmo†

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## Abstract

A remarkable theorem by Clifton, Bub and Halverson (2003) (CBH) characterizes quantum theory in terms of information-theoretic principles. According to Bub (2004, 2005) the philosophical significance of the theorem is that quantum theory should be regarded as a “principle” theory about (quantum) information rather than a “constructive” theory about the dynamics of quantum systems. Here we propose an alternative view according to which the philosophical significance of the CBH theorem lies in the predictions of quantum theory which remain hitherto *unobserved*, and in the empirical inequivalence between the constructive and the principle explanations thereof. We further challenge the principle information-theoretic view with a thought experiment that stems from this empirical inequivalence.

Keywords: Quantum information; Collapse theories; Crucial experiments; Principle vs. Constructive theories.

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\*Philosophy Department, University of Delaware, Newark, DE 19716 USA; Email: hagar@udel.edu

†Philosophy Department, University of Haifa, Haifa, Israel 31905; Email: meir@research.haifa.ac.il

# 1 Introduction

Quantum information theory has by now become to a large extent a new orthodoxy in the foundations of quantum mechanics. It is sometimes further claimed that the information-theoretic approach brings out the so-called “futility” of the long-standing debates over the interpretations of quantum mechanics.<sup>1</sup> A major conceptual tool enhancing the information-theoretic approach is the remarkable theorem by Clifton, Bub and Halverson (2003, CBH henceforth) according to which quantum theory can be characterized by three information-theoretic principles: no signaling, no broadcasting and no (unconditionally secure) bit commitment (NO BIT henceforth). The purpose of this paper is to examine the information-theoretic approach to quantum mechanics focusing on Bub’s (2004, 2005) recent analysis of it and some of its implications.

On the basis of the above three principles of the CBH theorem, Bub (2004, p. 242; see also 2005) argues for the following three theses:

1. A quantum theory is best understood as a theory about the possibilities and impossibilities of information transfer as opposed to a theory about the mechanics of nonclassical waves or particles.<sup>2</sup>
2. Given the three information-theoretic constraints, any mechanical theory of quantum phenomena that includes an account of the measuring instruments that reveal these phenomena must be empirically equivalent to a quantum theory.
3. Assuming the information-theoretic constraints are in fact satisfied in our world, any mechanical theory of quantum phenomena that includes an account of measurement interactions can be acceptable, and the appropriate aim of physics at the fundamental level then becomes the representation and manipulation of information.

In his recent paper in this journal, Bub (2005) depicts the philosophical significance of the CBH theorem as analogous to Einstein’s shift from the constructive view of theories—attributed to Lorentz and FitzGerald—towards

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<sup>1</sup>For such a claim see Fuchs (2002); For a response—Hagar (2003)

<sup>2</sup>By *information* Bub means information in the physical sense as measured, e. g., in quantum mechanics by the von Neumann entropy.

the principle view of theories in the context of the special theory of relativity (STR henceforth).<sup>3</sup> His idea is that the distinction between constructive theories and theories of principle is suitable to characterize the difference between the information–theoretic approach and all other interpretations of quantum theory. As the above theses show, Bub believes that if, indeed, the three information–theoretic principles of the CBH theorem hold in our world, then no constructive theory for quantum phenomena is possible that yields different predictions than those of quantum theory.

Agreeing as we do with Bub’s second thesis (that any constructive theory for quantum phenomena which satisfies the three information–theoretic principles of the CBH theorem is empirically indistinguishable from quantum theory) here we wish to present a somewhat different view on the philosophical significance of the CBH theorem.<sup>4</sup> As Bub (2004) himself notes (and in accord with his second thesis) a certain constructive theory for quantum phenomena, namely the collapse theory by Ghirardi, Rimini and Weber (GRW) *does* give different predictions from those of quantum theory, while violating the NO BIT constraint (above). However, this violation is compatible with everything we know empirically about the physical world. Roughly, the NO BIT constraint implies the *unrestricted* validity of the superposition principle, and in particular, it entails that macroscopic massive systems might be in nonlocal entangled EPR–type states even with respect to their spatial degrees of freedom. But the existence of such macrostates has never been experimentally confirmed, so we do not really know empirically whether or not they are physically possible. In this paper we focus only on collapse theories as constructive alternatives to Bub’s principle approach.<sup>5</sup> We shall

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<sup>3</sup>For more on the constructive approach to STR see Jánossy (1971) and Brown (2003).

<sup>4</sup>We set aside the more general issue of the aim of physics as stated by Bub’s third thesis. In this context it is interesting that Maxwell, although accepting the distinction between the physics of principles and the construction of models and even admitting that *in principle* indefinitely many dynamical models can explain certain phenomena, nevertheless devoted his career almost solely to the construction of such models (Harman 2001). Einstein himself, after promoting in 1905 the distinction he borrowed from Maxwell and Poincaré between principles and constructions, shifted back to the constructive view and later on abandoned what he called “the new fashion” which he himself helped creating (Balashov and Janssen 2003).

<sup>5</sup>We do not address here the subtler issue of whether or not Bohmian mechanics might be distinguished empirically from other no collapse theories such as modal and many worlds theories and Bub’s principle approach. We agree with Bub (2005) that Bohmian mechanics is empirically equivalent to no collapse quantum mechanics (but compare Valentini (2002)).

argue for the following alternative theses.

- I. Bub's principle information-theoretic approach and alternative constructive collapse theories, such as the GRW theory are *empirically* distinguishable. This is obvious but in the present context deserves attention.<sup>6</sup>
- II. Bub's information-theoretic construal of quantum theory on the basis of the CBH theorem—whatever merit it may carry—gives no reason for abandoning constructive dynamical theories, in particular theories which differ empirically from quantum mechanics under Bub's approach. The lesson one should take from the CBH theorem lies not in the quantum phenomena captured by its three information-theoretic principles, but rather in the *predictions* of quantum mechanics, given the general validity of the CBH constraints, which up to now remain *unobserved*.
- III. The information-theoretic approach to quantum mechanics is *incomplete* and must be supplemented by further principles over and above those suggested by the CBH theorem. In particular, the notion of quantum information cannot be taken as a primitive but rather requires a quantum mechanical analysis of measurement of the kind suggested by constructive theories.

The paper is structured as follows. We briefly review in Section 2 the CBH theorem and the purported philosophical significance Bub attaches to it. In Section 3 we explain how the GRW collapse theory bears on the CBH information-theoretic principles, focusing in particular on the NO BIT principle that Bub sees as constraining any constructive model for quantum phenomena (Section 3.1). In Section 3.2 we argue for thesis II above, namely that the issue at stake is different explanations of as yet *unobserved* quantum predictions. In Section 4, we focus on the empirical inequivalence between

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On the other hand, we note that questions of theory choice depend on quite complex factors and not only on empirical content.

<sup>6</sup>There are some definite suggestions of crucial tests between the GRW theory and standard quantum mechanics which bear on the implications of the different rates of GRW collapses and decoherence (see Adler 2005, Adler *et al.* 2005, Bassi *et al.* 2005, Hemmo and Shenker 2005).

the constructive GRW theory and information–theoretic approaches: we first challenge the latter with a thought experiment that establishes our thesis III above (Section 4.1); and we consider various possible replies to our argument in Section 4.2. Finally, in Section 5 we consider another often stated argument against collapse theories and explain why this argument is unacceptable.

## 2 The CBH Theorem and Its Philosophical Significance

The question raised by CBH is whether we can deduce the kinematic aspects of the quantum–theoretic description of physical systems from the assumption that we live in a world in which there are certain constraints on the acquisition, representation, and communication of information. CBH answered this question positively, supplying three information–theoretic principles (so-called three *no-go*’s) that are supposed to filter out the algebraic structure of operators and states that characterize quantum theory from the more basic structure of  $C^*$ -algebra.

The first principle, called *no signaling*, prohibits superluminal transfer of information between spacelike separated systems by carrying out measurements on one of them. In other words, no signaling says that measurements (and in fact any physical manipulation) confined to a remote system cannot possibly change the statistics of the outcomes of measurements that might be carried out on the local system. If Alice and Bob are two physically distinct systems,<sup>7</sup> then when both perform local measurements, Alice’s measurements can have no influence on the statistics of the outcomes of Bob’s measurements, and conversely. This result follows from the *no signaling* theorem in quantum mechanics according to which local measurements on a system  $\alpha$  have no effect whatsoever on the reduced state of a remote system

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<sup>7</sup>Consider a composite quantum system A+B, consisting of two subsystems, A and B. For simplicity, assume the systems are identical, so their  $C^*$ -algebras  $\mathfrak{A}$  and  $\mathfrak{B}$  are isomorphic. The observables of the component systems A and B are represented by the self-adjoint elements of  $\mathfrak{A}$  and  $\mathfrak{B}$ , respectively. Let  $\mathfrak{A} \vee \mathfrak{B}$  denote the  $C^*$ -algebra generated by  $\mathfrak{A}$  and  $\mathfrak{B}$ . To capture the idea that A and B are *physically distinct* systems, we assume (as a necessary condition) that any state of  $\mathfrak{A}$  is compatible with any state of  $\mathfrak{B}$ , i.e., for any state  $\rho_A$  of  $\mathfrak{A}$  and  $\rho_B$  of  $\mathfrak{B}$ , there is a state  $\rho$  of  $\mathfrak{A} \vee \mathfrak{B}$  such that  $\rho|_{\mathfrak{A}} = \rho_A$  and  $\rho|_{\mathfrak{B}} = \rho_B$ .

$\beta$  no matter what the quantum state of  $\alpha + \beta$  is. (see Ghirardi *et al.* 1980).

The second principle, called *no broadcasting*, prohibits perfectly broadcasting the information contained in an unknown physical state.<sup>8</sup> No broadcasting ensures that the individual algebras  $\mathfrak{A}$  and  $\mathfrak{B}$  of the two distinct physical systems are noncommutative. As CBH show, broadcasting and cloning are always possible for classical systems, i.e., in commutative  $C^*$ -algebra there is a universal broadcasting map that clones any pair of input pure states and broadcasts any pair of input mixed states. Conversely, they show that if any two states can be (perfectly) broadcast, then any two pure states can be cloned; and if two pure states of a  $C^*$ -algebra can be cloned, then they must be orthogonal. So, if any two states can be broadcast, then all pure states are orthogonal, from which it follows that the algebra is commutative. In elementary quantum mechanics, on the other hand, neither cloning nor broadcasting is possible in general.

These two principles capture two well known features of quantum theory: for a composite system A+B, the no signaling constraint entails that the  $C^*$ -algebras  $\mathfrak{A}$  and  $\mathfrak{B}$ , whose self-adjoint elements represent the observables of A and B, commute with each other (this feature is sometimes called ‘micro-causality’); and the no broadcasting constraint entails that each of the algebras  $\mathfrak{A}$  and  $\mathfrak{B}$  are noncommutative. The quantum mechanical phenomenon of interference is the physical manifestation of the noncommutativity of quantum observables or, equivalently, the superposition of quantum states.

The third NO BIT principle prohibits communicating information in a way that implements a given ‘bit commitment’ with *unconditional* security.<sup>9</sup> In quantum mechanics Alice may send Bob, as a warrant of her bit commitment, one of *two* mixtures associated with the same density operator (where the mixtures correspond to alternative commitments). However, Alice may prepare in advance a suitable entangled state, where the reduced density

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<sup>8</sup>In fact, for pure states, broadcasting reduces to cloning. In cloning, a ready state  $\sigma$  of a system B and the state to be cloned  $\rho$  of system A are transformed into two copies of  $\rho$ . In broadcasting, a ready state  $\sigma$  of B and the state to be broadcast  $\rho$  of A are transformed to a new state  $\omega$  of A+B, where the marginal states of  $\omega$  with respect to both A and B are  $\rho$ .

<sup>9</sup>Bit commitment is a cryptographic protocol in which, say, Alice sends an encoded bit to Bob as a record of her commitment to either 0 or 1, which allows Bob to ascertain Alice’s bit commitment later (only with further information supplied by Alice) so as to make sure that her initial commitment hasn’t changed. In classical information theory unconditionally secure bit commitment is always possible in principle.

operator for Bob is the same as that of the mixture she sent him. In this case Alice would be able to steer Bob's system nonlocally into either one of the two mixtures (where Bob cannot be aware of this). So if there are no restrictions on the entangled states that Alice may prepare, Alice can always cheat Bob by pretending to have a secure bit commitment. The NO BIT constraint prohibits unconditionally secure bit commitment by precisely stipulating that there are no restrictions on the preparation and stability of entangled nonlocal states. Note that the structure that the first two principles filter out from the general  $C^*$ -algebra still includes noncommutative theories which are compatible with unconditionally secure bit commitment. In such theories, it might be, for example, that although nonlocal entangled states (i. e., states which permit remote steering) are physically possible, they turn out to be as a matter of fact highly unstable (over time) and therefore not feasible.<sup>10</sup> So one has to stipulate the feasibility of such states, and this is what the NO BIT constraint does.

Taking stock, the content of the CBH theorem, according to Bub (2005), is this:

... [Q]uantum theories—theories where (i) the observables of the theory are represented by the self-adjoint operators in a noncommutative  $C^*$ -algebra (but the algebras of observables of distinct systems commute), (ii) the states of the theory are represented by  $C^*$ -algebraic states (positive normalized linear functionals on the  $C^*$ -algebra), and spacelike separated systems can be prepared in entangled states that allow remote steering, and (iii) dynamical changes are represented by completely positive linear maps—are characterized by the three information-theoretic 'no-go's': no superluminal communication of information via measurement, no (perfect) broadcasting, and no (unconditionally secure) bit commitment.

In order to flesh out the philosophical significance of the CBH theorem, Bub (2005) makes use of the famous distinction between theories of principles and constructive theories. According to this distinction (which is attributed usually to Einstein although it already appears in the writings of Maxwell and Poincaré),

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<sup>10</sup>As noted by Bub, such a possibility in which an entangled state of a composite system quickly decays to a mixture as soon as the component systems spatially separate was raised by Schrödinger in 1936.

[constructive theories] attempt to build up a picture of the more complex phenomena out of the materials of the relatively simple formal scheme from which they start out. Thus the kinetic theory of gases seeks to reduce mechanical, thermal and diffusional processes to the movement of molecules—i.e., to build them up of the hypothesis of molecular motion. [Principle theories, on the other hand,] . . . employ the analytic, not the synthetic method. The elements which form their basis and starting point are not hypothetically construed but empirically discovered ones, general characteristics of natural processes, principles that give rise to mathematically formulated criteria which the separate processes or the theoretical representations of them have to satisfy. Thus the science of thermodynamics seeks by analytical means to deduce necessary conditions which separate events have to satisfy, from the universally experienced fact that perpetual motion is impossible (Einstein 1919).

In his analysis of quantum mechanics as a principle theory, Bub appeals to two different historical analogies where scientific progress has been clearly achieved. In his (2004) he considers the transition from the constructive ether-theory of Lorentz–FitzGerald to the abstract geometric formalism of Minkowski’s spacetime and argues that the transition was only made possible by Einstein’s principle approach to special relativity. And in (2005) Bub focuses on the transition (in the ‘opposite’ direction) from thermodynamics (as a sort of a principle theory) to the constructive theory of statistical mechanics (in the special case of the kinetic-molecular theory). In both cases we agree with Bub’s historical analysis, but we are doubtful as to the conclusions he draws about quantum mechanics. Bub argues that the CBH theorem plays the same role in a principle approach to quantum mechanics as the one played by Einstein’s principle approach to relativity theory. Focusing on Bohmian mechanics as a constructive mechanical model of quantum mechanics, Bub’s argument consists of essentially three elements: First, in special relativity the structure of spacetime is understood in terms of a new primitive—i. e., a *field*—which is not reducible to mechanical motion (e. g., of particles relative to the ether as in the Lorentz theory). Similarly, in quantum mechanics, the algebraic structure of observables is understood in terms of a new primitive, i. e., *quantum information* not reducible to the behavior of mechanical systems (e. g., particle trajectories in configuration space).



Second, in both cases the principle approaches are simpler and more fruitful. In the case of quantum theory the CBH theorem is taken to explain *away* (using the above constraints on information flow) some problematic notions in Bohmian mechanics such as sourceless fields that guide the trajectories of particles in configuration space (that sometimes even result in e. g., surreal trajectories and contextual probabilities). At the same time the information-theoretic approach brings out new implications of quantum mechanics such as the use of entanglement as a new physical resource for quantum computation. Third, and most crucially in the present context, the constructive mechanical alternatives to quantum theory are *empirically* indistinguishable from the principle theories.

The point of Bub's second analogy (i. e., the transition from thermodynamics to the kinetic-molecular theory) is precisely to bring out the immense importance of empirical distinguishability in theory choice. Here the argument is that the kinetic-molecular theory would not be regarded seriously as an alternative constructive model for thermodynamics if (contrary to fact) it had no new empirical predictions that differ from those of thermodynamics, and if those predictions were not experimentally confirmed (e. g., Einstein's prediction of fluctuations in Brownian motion). By contrast, in the case of Bohmian mechanics it is provable that (i) once the distribution of the particles' positions is given by the square of the amplitude of the wavefunction at each point (i. e., by the Born probabilities) this distribution is preserved at all later times by the dynamical equations of motion (see Dürr, Goldstein and Zanghi 1992); and (ii) given the Born distribution, Bohm's theory is empirically equivalent to quantum mechanics. This means, in the information-theoretic approach, that Bohm's theory must be equivalent to quantum theory if the CBH constraints on the information flow were satisfied even once in the past (since, roughly, in a no collapse theory these constraints hold if and only if the Born probability distribution holds). Consequently, Bohm's theory, quite unlike the case of Brownian motion, can yield no predictions of 'fluctuations' that deviate from the predictions of quantum mechanics. And therefore, given Bub's arguments above, the rational epistemological stance, is to reject it, and prefer the principle information-theoretic approach as suggested by the CBH theorem.

In what follows we question Bub's reading of the present state of affairs in quantum mechanics. Although we largely agree with Bub's analysis (sketched above) of the features of alternative hidden variables theories, we think that the analysis doesn't capture all the relevant aspects related to theory choice

in the case of the present state of quantum mechanics. In particular, there are two crucial points that seem to us not appropriately addressed in Bub’s analysis. First, there are *other* constructive quantum mechanical theories (in particular the GRW *collapse* theory) which generally violate the NO BIT constraint (at least as a stable constraint; see below). The GRW theory differs in its empirical predictions from quantum theory, while it is perfectly compatible with our experience so far. By Bub’s own standards (see Bub 2005, Sec. 4), therefore, the GRW theory is acceptable as an alternative constructive theory. But adhering to Bub’s principle approach would result in losing sight of theories like the GRW theory on what seems like an *a-priori* rather than an empirical basis. Second, information–theoretic approaches (i. e., both Bub’s principle approach and the Bayesian approach) are *incomplete*, and as we said (in our thesis (iii) above) need be supplemented by further principles that are quite hard to justify (see Section 4). On the basis of these two points we now proceed to argue for our thesis (ii), namely that the issue at stake lies not in the information–theoretic description of the *observed* quantum phenomena, but rather in the explanation of the predictions of quantum theory which up to now remain *unobserved*.

### 3 Explaining the *Unobserved*

Standard no collapse quantum theory predicts the unrestricted existence of superpositions in spatially separated entangled states. This is tantamount to saying, using the CBH theorem, that *ex hypothesis* the NO BIT principle holds in our world. But then, given this hypothesis, one question that arises naturally is: why do superpositions remain *unobserved* in macroscopic massive physical systems?

This question is in fact a variant on the so-called measurement problem in the quantum theory of measurement. In this context the problem arises as a straightforward consequence of applying the Schrödinger linear and deterministic dynamics to the measurement interaction. As is well known the Schrödinger dynamics results for a generic measurement in a superposition of the form

$$|\Psi\rangle = \sum_i \mu_i |\psi_i\rangle \otimes |\varphi_i\rangle, \quad (1)$$

where the kets  $|\psi_i\rangle$  represent some suitably defined pointer states of the measuring apparatus (typically, the  $|\psi_i\rangle$  are eigenstates of the pointer position),

and the  $|\varphi_i\rangle$  are some states of the system. The problem is that in states of the form (1) the measurement has no definite outcome (except in the special case where all but one of the  $\mu_i$  are zero), since the final (reduced) state of the apparatus cannot in general be described in terms of an ensemble of systems in a classical mixture (in which the  $|\mu_i|^2$  represent the probabilities for each  $|\psi_i\rangle$  to actually occur).

The information–theoretic approach addresses this problem by appealing to models of decoherence in which the interaction of relatively massive systems with their environment brings about a so-called *effective* collapse onto the eigenstates of some preferred observables (typically, position).<sup>11</sup> According to this approach (called by Bub 1997 some years ago the ‘new orthodoxy’) macroscopic entangled states in position exist, but for all practical purpose they are unobserved because we have no control over the states of the environment, so that the reduced state of a decohering system is practically indistinguishable from a classical mixture. That this is no solution to the measurement problem was argued in the past by many,<sup>12</sup> including Bub himself in the context of (constructive) hidden variables theories.<sup>13</sup> However, Bub seems to think that the objection does not apply to his own principle information–theoretic approach. We disagree and will argue for this in Section 4. But before doing so, we wish to consider here the constructive collapse theory by GRW that gives a clear and distinct solution to the measurement problem and explains the *unobservability* of macroscopic spatial superpositions in the most straightforward way.

### 3.1 The Collapse Theory of GRW

The GRW theory (formulated for non–relativistic quantum mechanics) explains the *unobservability* of some macroscopic superpositions of *position* states by modifying the Schrödinger linear dynamics in such a way that given the new dynamics such superpositions are overwhelmingly likely to collapse

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<sup>11</sup>For standard models of decoherence, see Joos *et al.* (2003) and references therein.

<sup>12</sup>E.g., Bell (1990), and recently Adler (2003).

<sup>13</sup>As Bub puts it in his (2000, 90–91): the fact that the ‘effective’ quantum state—an improper mixture described by the reduced density operator (obtained by tracing out the degrees of freedom of the environment)—is diagonal with respect to properties associated with some pointer basis “not only fails to account for the occurrence of just one of these [properties] but is actually inconsistent with such occurrence”, since taking into account the environment gives us back the pure state from which the mixture was derived, and this state is inconsistent with the occurrence of events associated with definite properties.

at every moment of time, and in this sense they are highly unstable. The Schrödinger equation is changed by adding to it a non-linear and stochastic term that induces the so-called *jump* or collapse of the wavefunction. The jump is supposed to occur on occasion in position space and its postulated frequency is proportional roughly, to the mass density of the system (or in Bell's (1987) model on the number of particles described by the wavefunction). For our purposes it is enough to sketch Bell's (1987) version of the elementary and non-relativistic theory of GRW. This goes roughly as follows.

Consider the quantum mechanical wavefunction of a composite system consisting of  $N$  particles:

$$\psi(t, \mathbf{r}_1, \mathbf{r}_2, \dots, \mathbf{r}_N). \quad (2)$$

The time evolution of the wavefunction usually (at almost all times) satisfies the deterministic Schrödinger equation. But sometimes *at random* the wavefunction collapses or *jumps* onto a wavefunction  $\psi_\ell$  localized in position of the (normalized) form

$$\psi_\ell = \frac{j(\mathbf{x} - \mathbf{r}_n) \psi(t, \mathbf{r}_1, \mathbf{r}_2, \dots, \mathbf{r}_N)}{R_n(\mathbf{x})}, \quad (3)$$

where  $\mathbf{r}_n$  in the jump factor  $j(\mathbf{x} - \mathbf{r}_n)$  (which is normalized) is randomly chosen from the arguments  $\mathbf{r}_1, \dots, \mathbf{r}_n$  of the wavefunction immediately before the jump, and  $R_n(\mathbf{x})$  is a suitable renormalization term. For  $j$ , GRW suggest the Gaussian:

$$j(\mathbf{x}) = K \exp(-\mathbf{x}^2/2\Delta^2), \quad (4)$$

where the width  $\Delta$  of the Gaussian is supposed to be a new constant of nature:  $\Delta \approx 10^{-5}$ cm.

Probabilities enter the theory twice. First, the probability that the *collapsed* wavefunction  $\psi_\ell$  after a jump is centered around the point  $\mathbf{x}$  is given by

$$d^3\mathbf{x} |R_n(\mathbf{x})|^2. \quad (5)$$

This probability distribution, as can be seen, is proportional to the standard quantum mechanical probability given by the Born rule for a position measurement on a system with the wavefunction  $\psi(t, \mathbf{r})$  just prior to the jump. Second, the probability in a unit time interval for a GRW jump is

$$\frac{N}{\tau}, \quad (6)$$

where  $N$  is the number of arguments in the wavefunction (i.e., in Bell's model it may be interpreted as the number of particles), and  $\tau$  is, again, a new constant of nature ( $\tau \approx 10^{15}$  sec  $\approx 10^8$  year). Note that the expression (6) does not depend on the quantum wave function, but only on  $N$ . This is essentially the whole theory.

It is easily seen that for microscopic systems GRW collapses have extremely low probability to occur, so that the quantum mechanical Schrödinger equation turns out to be literally true at almost all times in just the way that no collapse quantum mechanics predicts (and experiment confirms). However, for massive macroscopic systems (e.g., for systems with  $10^{23}$  particles) the GRW collapses are highly probable at all times. In measurement situations the GRW theory implies that superpositions of macroscopically distinguished pointer states of the form (1) collapse with extremely high probability onto the localized states  $|\psi_i\rangle$  on time scales that are much faster than measurement times. In particular, the probability that the wavefunction of the composite of system plus apparatus will stay in the superposition (1) for more than a fraction of a second (e.g., by the time the measurement is complete) vanishes exponentially. So the GRW jumps reduce wavefunctions of the form (1) to one of the components  $|\psi_i\rangle \otimes |\varphi_i\rangle$ , in which the pointer is in the *localized* state  $|\psi_i\rangle$ , where the probability for a collapse onto the  $i$ -th term (see equation (5)) is given as usual by the squared amplitude  $|\mu_i|^2$ . This means that in a sequence of quantum mechanical measurements the GRW jumps result in definite outcomes with frequencies that are (approximately) equal to the Born-rule probabilities  $|\mu_i|^2$ . The measurement problem is solved as long as measurements involve a macroscopic recording of the measurement outcome in *position* (e.g., a moving pointer of a measuring device, particles hitting on macroscopically separated regions of a computer screen, etc.). Note that, and this is important for our discussion below, the GRW jumps are designed to be extremely effective *only* for macroscopic superpositions of *position* states (and to any other states that are *coupled* to positions), but *not* to arbitrary superpositions.

There are well known physical weaknesses in the GRW theory. In the non-relativistic case the problem seems to be how to avoid the accumulated violations of conservation of energy induced by the jumps.<sup>14</sup> But perhaps the main problem is to write down a relativistic formulation of the GRW theory.

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<sup>14</sup>See Ghirardi (2000) and references therein; Some progress is reported in Bassi *et al.* (2005b)

Although GRW give the same predictions as standard quantum mechanics with respect to the nonlocal correlations in EPR–Bell–type experiments, the problem is that it is not clear whether in a relativistic version of the GRW dynamics the jumps could be made Lorentz–covariant.<sup>15</sup> Also, it has been argued against GRW that the theory appears to be strongly *ad hoc* as it allows free adjustments of constants in order to be in agreement with experiments. Here, however, we set these important issues aside, because we are not concerned with the GRW theory *per se*, nor with its comparison with other constructive theories. Rather, our focus is whether Bub’s principle approach which seems to *rule out* the GRW theory on the basis of information–theoretic constraints is acceptable.

### 3.2 Constructing the Principles

How does the GRW theory fare with the information–theoretic constraints of the CBH theorem? The first thing to say is that the GRW theory does not violate the first two constraints (i.e., no signaling and no broadcasting) because of its stochastic dynamics (see, e.g., Gisin 1989). But, in accord with Bub’s analysis, the GRW theory does violate the NO BIT principle in the following sense. It predicts that superpositions of macroscopically distinguishable *position* states decay extremely quickly by the GRW dynamics into the corresponding mixtures. Obviously, GRW do not introduce any sort of superselection rules. The theory allows one to prepare *any* system in *any* quantum state, and any pair of systems in any entangled and nonlocal state (say, of the EPR–Bell–type) whatsoever. In particular, one may prepare, for example, a superposition of highly entangled spin states even for a macroscopic number of particles that will be quite stable over a significant time interval (e.g., as in the spin–echo experiments, where the spins get, as it were, in and out of entangled states during an appreciable time interval; see Hemmo and Shenker 2005). Such states are perfectly compatible with the GRW dynamics. Moreover, one may even prepare *any* state of two massive molecules in an entangled EPR–state over their positions. But, given the GRW dynamics, states of this latter sort would be highly unstable due to the extremely fast rates of the GRW jumps. More generally, it is an empirical prediction of the GRW theory that superpositions of entangled position states of spatially separated systems are highly unstable if the systems are

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<sup>15</sup>But see Ghirardi (2000) and Myrvold (2002).

massive enough. Hence, observable effects of such superpositions are hard to come by, and under normal circumstances, unobserved.

So the crucial point for our discussion is this. The violation of the NO BIT constraint by the GRW theory is one indication that the theory is not empirically equivalent to standard no collapse quantum mechanics. That is, in the GRW theory an unconditionally secure bit commitment could always be made possible via a set up that requires Alice to encode her bit commitment in the position state of a massive enough system. However, when one introduces the NO BIT constraint in the information–theoretic approach one implicitly presupposes that as a matter of fact the entangled states one works with are states of *micro*systems, say, over spin degrees of freedom. For such states we have ample experimental confirmation that the NO BIT constraint is, indeed, satisfied. But for such states *also* the GRW theory satisfies the NO BIT constraint with extremely high probability. It violates the NO BIT constraint only with respect to superpositions of macroscopically distinguishable position states. But for such *macro*states also standard no collapse quantum theory predicts an *effective* violation of the NO BIT constraint due to environmental decoherence (i. e., such states effectively collapse also in the standard theory as all models of environmentally induced decoherence show; see e. g., Zurek 1991, Joos *et al.* 2003).

So practically, no collapse quantum mechanics and the GRW theory agree on the NO BIT constraint for all cases in which there are good empirical reasons to believe it is true. And the two theories disagree about the NO BIT constraint only with respect to those macro superpositions about which we do not know whether or not they in fact exist in our world. But of course this is no surprise since this disagreement is located precisely where the two theories differ in their empirical predictions. So we are back to square one! The CBH theorem provides an elegant formulation of the difference *in principle* between theories of genuine collapse and theories of effective collapse (as in situations of environmentally induced decoherence). But given what we know empirically about the world, there seem to be no grounds for adopting the NO BIT principle as an unrestrictive constraint on theory choice.<sup>16</sup>

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<sup>16</sup>Note that the point made here is quite general: it would be applicable to *any* information–theoretic characterization of the mathematical structure of quantum theory (e. g., Spekkens 2004) and to any constructive alternative of it, provided the latter is empirically well confirmed and *not* equivalent to standard quantum mechanics.

## 4 Inconsistent Predictions?

We now proceed to argue for our thesis III, namely that information–theoretic approaches to quantum mechanics are *incomplete* and need be supplemented by further axioms that exceed information–theoretic principles such as those suggested by the CBH theorem, or by subjectivist Bayesian approaches to quantum mechanics (see e. g., Fuchs and Peres 2000, Fuchs 2002, Caves *et al.* 2002, Spekkens 2004, and references therein). For convenience, we shall frame our discussion in the context of the Bayesian approach. After presenting our argument in the form of a thought experiment, we shall make the link to Bub’s principle approach.

The Bayesian approach to quantum theory is based on an epistemic attitude according to which the quantum state does not represent a real physical state of a system, but instead supplies an observer with statistical information concerning all possible distributions of measurement results. The probabilities computed by the standard Born rule are understood as probabilities of *finding* the system on measurement in some specific state. Applying Von Neumann’s projection postulate to the quantum state (or more generally applying Lüder’s rule), under this account, is just an adjustment of subjective probabilities, conditionalizing on newly discovered results of measurement, i. e., it is merely a change in the observer’s knowledge, or probability assignments. By contrast, the unitary and linear quantum mechanical dynamics (i. e., the Schrödinger equation in the non-relativistic case) describes the observer–independent and in this sense objective time evolution of the quantum probabilities when no measurement takes place. Hence, in this approach measurements can be treated operationally as ‘black boxes’ and require no further theoretical analysis.

### 4.1 A thought experiment

We now turn to our thought experiment which is a variant on Wigner’s friend. Consider the following set–up in which an observer  $A$  measures the  $z$ –spin of a spin-half particle  $P$  by means of a Stern–Gerlach apparatus (which, to keep things simple, we omit from our description below). The quantum state of  $P + A$  initially is

$$|\Psi_0\rangle = (\alpha|+_z\rangle + \beta|-_z\rangle)|\psi_0\rangle_A \tag{7}$$



where  $|\alpha|^2 + |\beta|^2 = 1$  ( $\alpha, \beta \neq 0$ ), the kets  $|\pm_z\rangle$  are the  $z$ -spin eigenstates and  $|\psi_0\rangle$  is the initial *ready* state of  $A$ . After the measurement, in a no collapse theory, the quantum mechanical state of  $P + A$  is the superposition:

$$|\Psi_1\rangle = \alpha|+_z\rangle|\text{see up}\rangle_A + \beta|-_z\rangle|\text{see down}\rangle_A \quad (8)$$

where  $|\text{see up}\rangle_A$  and  $|\text{see down}\rangle_A$  are, say, the brain states of  $A$  corresponding to her perceptions and memories of the two possible outcomes of the measurement. By contrast, in a collapse theory of the GRW kind, the state (8) is highly unstable (assuming that the chain of interactions leading to  $A$ 's different memory states involves macroscopically distinguishable position states), so that by the time the measurement is complete this state collapses onto one of its components.

Consider now an observable  $\hat{O}$  of the composite system  $P + A$  of which the state (8) is an eigenstate with some definite eigenvalue, say  $+1$ .<sup>17</sup> Suppose that the composite system  $P + A$  is completely isolated from the environment, and that a measurement of  $\hat{O}$  is about to be carried out on  $P + A$  immediately after the state (8) obtains. According to no collapse quantum mechanics the measurement of  $\hat{O}$ , under these circumstances, is completely non-disturbing in the sense that after the measurement the state of  $P + A$  remains precisely as in (8). One may think of  $\hat{O}$  as an observable that is maximally sensitive to whether or not the interference terms between the different components of (8) exist. In other words, the measurement of  $\hat{O}$  on  $P + A$  if the state (8) is the true state of  $P + A$  is a non-demolition measurement that, as it were, passively *verifies* whether or not  $P + A$  is in fact in that state.

Note that  $\hat{O}$  commutes neither with the  $z$ -spin nor with  $A$ 's perceptions and memories of the outcomes of the  $z$ -spin measurement. This surely raises interesting questions about the status of the uncertainty relations in this set up and about the reliability of  $A$ 's memories of the outcome of her spin measurement in the event that  $A$  measures  $\hat{O}$  just after her spin measurement. However, no matter what happens during the measurement of  $\hat{O}$  (to  $A$ 's memory of the outcome of her spin measurement, or to the  $z$ -spin values themselves) quantum mechanics implies that the *correlations* between the  $z$ -spin of  $P$  and  $A$ 's memories must remain exactly the same as they were

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<sup>17</sup>Observables like  $\hat{O}$  are defined in the tensor product Hilbert space  $\mathcal{H}_P \otimes \mathcal{H}_A$  unless superselection rules are introduced. For our purposes think of  $\hat{O}$  as an observable that pertains to  $P$ 's spin degree of freedom and the relevant degrees of freedom of  $A$ 's sense organs, perceptions, memory, etc.

before the  $\hat{O}$ -measurement. Moreover, in a no collapse theory, the state of  $P+A$  immediately after the  $\hat{O}$ -measurement will be, with complete certainty, just:

$$|\Psi_2\rangle = \alpha|+_z\rangle|\text{see up}\rangle|\text{see } \hat{O} = +1\rangle + \beta|-_z\rangle|\text{see down}\rangle|\text{see } \hat{O} = +1\rangle \quad (9)$$

where  $|\text{see } \hat{O} = +1\rangle$  is the state corresponding to perceiving the result of the  $\hat{O}$ -measurement.

By contrast, in a collapse theory of the GRW kind, the state of  $P+A$  *immediately* after the  $\hat{O}$ -measurement will be given by *one* of the eigenstates of  $\hat{O}$ , where the probability that it will be state (8), and therefore that the outcome  $\hat{O} = +1$  will be obtained, is only  $|\alpha|^2$ . Note that even if that outcome will obtain, the state (8) will extremely quickly collapse, again, onto one of the components of state (8) with probabilities that are given by  $|\alpha|^2$  and  $|\beta|^2$ . So, in the GRW theory, the final value of the  $z$ -spin and the spin memory of  $A$  might be different before and after the  $\hat{O}$ -measurement.

Note further that we deliberately do not specify here *who* carries out the  $\hat{O}$ -measurement (i. e., in which degree of freedom the outcome  $\hat{O} = +1$  is recorded). It may be carried out by  $A$  or by some other observer  $B$  external to  $A$ 's laboratory. As can be seen from our notation in (9), we have implicitly assumed (for the sake of simplicity only) that the outcomes of  $A$ 's spin measurement and of the  $\hat{O}$ -measurement are recorded in *separate* degrees of freedom. But in fact our argument below does not depend on this assumption. Quantum mechanics itself imposes no restrictions whatsoever on the way in which the outcomes of these measurements are recorded, except that they cannot be recorded *simultaneously* in the same degree of freedom (since  $\sigma_z \otimes \mathbf{1}$  as well as  $A$ 's memory observable are incompatible with  $\hat{O}$ ). Moreover, quantum mechanics (with or without collapse) imposes no further restrictions on the *identity* of the observers who may or may not carry out  $\hat{O}$ -type measurements.<sup>18</sup> We return to this point below.

To make things simple, let us suppose that the  $\hat{O}$ -measurement is to be carried out by the external observer  $B$ . But now we can ask  $A$  to give her *predictions* of the probabilities of the outcomes of the  $\hat{O}$ -measurement.<sup>19</sup> But

<sup>18</sup>See Albert (1983) for an extended discussion of  $\hat{O}$ -type measurements and their implications. Aharonov and Albert (1981) use  $\hat{O}$ -type measurements in their discussion of the collapse of the quantum state in a relativistic setting.

<sup>19</sup>Clearly, in quantum mechanics the quantum state assigned to a system is supposed to give the probabilities of the outcomes for *all* possible measurements.

here we encounter a problem in the information-theoretic approach since it doesn't tell us on what quantum state should  $A$  base her predictions.

In order to calculate her expected probabilities  $A$  may choose one of the following two options.

- (a) Update her quantum state in accordance with the outcome of the spin measurement she actually observed, either  $|\text{see up}\rangle_A$  or  $|\text{see down}\rangle_A$ . In this case, she would collapse the state (8) onto one of its spin+memory components. Applying the Born rule to this state, she will predict that the result of the  $\hat{O}$ -measurement will be  $+1$  with probability  $|\alpha|^2$ .
- (b) Ignore the outcome of the spin measurement she actually observed, and conditionalize her probabilities on the *uncollapsed* state as in (8). In this case, since the state in (8) is an eigenstate of  $\hat{O}$  with eigenvalue  $+1$ , she will predict that the result of the  $\hat{O}$ -measurement will be  $+1$  with *certainty* (i. e., probability 1).

But by carrying out a series of repeated  $\hat{O}$ -measurements on identically prepared systems, all in state (8), we can distinguish experimentally between the two predictions. Now, since we do not know whether or not post-measurement states of the form (8) actually collapse, we do not know which of these two predictions is correct. But, surely, they cannot be both true, since they are inconsistent.

The point to be made here, however, is that the information-theoretic approach gives no plausible account of *which* option is the correct one. On the one hand, the full information about the lab available to  $A$  before the  $\hat{O}$ -measurement is given by the *collapsed* state, and this justifies option (a). On the other hand, if  $A$  knows quantum mechanics under the information-theoretic approach, she believes that there is no real collapse of the state in measurement, and so her predictions ought to be guided in this case by the *uncollapsed* state as in (8). That is, on this view option (b) is justified. So the two predictions seem to be on equal footing.

We have formulated the above argument in terms of the Bayesian information-theoretic approach. The link to Bub's principle approach goes as follows. In both approaches quantum mechanical measurements are construed *operationally* as 'black boxes' with no further analysis. This is precisely the sense intended by Bub (2005, Sec. 4) of taking quantum information as a primitive and irreducible physical concept. As argued by Bub, once we accept the three constraints suggested by the CBH theorem, it follows

that measurements are to be treated operationally and measuring apparatuses as black boxes. But what our thought experiment above shows is that once we treat measurements operationally, the assignment of quantum states becomes (in some circumstances) ambiguous, and this ambiguity leads to inconsistent probability assignments to measurement outcomes!

## 4.2 Some resolutions

The above ambiguity in the state assignment must be resolved. In what follows we examine various possible ways in which a sophisticated proponent of the information-theoretic approaches might try to counter the above argument.

**(i)  $\hat{O}$ -type measurements are not feasible.** As a matter of fact, the  $\hat{O}$  measurement is physically impossible to carry out due to decoherence and the complexity of the set-up under consideration. As far as our best neurophysiological theories tell us, the sensory apparatus and brain processes of a human observer involved in typical perception and memory processes are *macroscopic* and subject to continuous decoherence (induced by interactions in and outside of the brain) that cannot be screened off. Consequently,  $\hat{O}$  will become extremely fast the wrong observable to measure in order to detect the interference terms in states of the form of (8). Moreover, even if one could identify the right observable to measure at a given time we cannot expect to have control over all the relevant degrees of freedom in and outside the observer's brain.

**Reply** Obviously,  $\hat{O}$ -type measurements are extremely hard to carry out and need be continuously protected against decoherence. This is much beyond our experimental reach. In fact, even if we set decoherence aside,  $\hat{O}$ -type measurements are not quite feasible in microscopic superpositions over, say, only spin degrees of freedom (since we need to measure total spin without measuring the spin components separately in order for the measurement to be non-disturbing). But ways to overcome such problems may be found. For example, in spin-echo experiments we know today by means of macroscopic manipulations only how to screen-off the effects of decoherence for appreciable time intervals (see Hemmo and Shenker 2005). Moreover, feasibility considerations are quite beside the point in the present context. Quantum mechanics allows  $\hat{O}$ -type measurements, and the above ambiguity need be resolved independently of whether we can or cannot practically translate it into an experimental context. Obviously, it may turn out that, on the basis

of some new physics, e.g., quantum gravity, the  $\hat{O}$ -measurement would be impossible *in principle* on pain of violating certain new physical laws, but as far as standard quantum theory is concerned, this is not the case.

**(ii) Options (a) and (b) are compatible.** There is no inconsistency, because  $A$ 's different predictions are computed on the basis of *different* quantum states (which may correspond to different points of views, different amounts of information, etc.). Take for example the EPR set-up, and suppose that only the observer on the left wing has measured the spin of the nearby particle. The predictions of the two observers differ: the observer on the left knows with certainty the result that would obtain on the right, whereas the observer on the right can only assign probability of one-half to his upcoming measurement.<sup>20</sup> But surely differences in probability assignments which are merely due to ignorance need not be problematic. This is exactly the situation in the above thought experiment.

**Reply** The situation in the context of the  $\hat{O}$ -measurement is entirely different. In EPR-type situations the information-theoretic view *does* pick out which observer gets it right: surely, the prediction of the observer on the left who's measured the spin of his particle is the more accurate one. Obviously, the observer on the right will update her probability assignment once she is informed about the outcome of the left measurement. But in our contraption above,  $A$  already knows everything there is to know about the  $z$ -spin in her lab before the  $\hat{O}$  measurement, so there is no question of information transfer from  $B$  to  $A$ .<sup>21</sup>

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<sup>20</sup>A similar argument can be made in the case of observers carrying out repeated measurements on the same system.

<sup>21</sup>One can ask: what would happen if  $A$  were to communicate her outcome to  $B$ ? Note first that it is quite plausible to say that as long as  $B$  does not know the outcome of  $A$ 's spin measurement,  $B$ 's predictions for the  $\hat{O}$  measurement ought to conform to option (b) (but see below). So  $B$ 's predictions are not ambiguous (unlike  $A$ 's predictions). What about  $A$ 's predictions? Once  $A$  communicates her spin outcome to  $B$ ,  $A$ 's predictions about the  $\hat{O}$ -measurement would no longer be ambiguous, since the reduced state of  $P + A$  after  $A$ 's communication with  $B$  would be given by the mixture corresponding to the state (8) (and the total state of  $P + A + B$  would no longer be an eigenstate of  $\hat{O}$ ). In fact, the predictions of  $A$  and  $B$  would coincide in this case; that is, both would predict probability of one-half to the outcome  $\hat{O} = +1$ . But, quantum mechanics entails the existence of *other*  $\hat{O}$ -type observables (e.g., any observable  $\hat{O}_2$  of which the state of  $P + A + B$  immediately after the interaction of  $A$  and  $B$  is an eigenstate) with respect to which we can run the *same* argument again, this time on the predictions of both  $A$  and  $B$ . And likewise *ad infinitum*. But now the crucial point is that whether or not  $A$  communicates her outcome to  $B$  is completely beside the point (we return to this point below). Suppose that  $A$  doesn't.

**(iii) Option (b) is wrong.**  $A$  should stick to option (a) and use her spin–memory eigenstate in order to calculate her probabilities (likewise for the external observer  $B$ ). By construction, the above set–up stipulates that  $A$  carried out a *measurement*, and therefore from  $A$ ’s point of view the state in (8) has collapsed. As to  $B$ , although he doesn’t know which outcome  $A$  has observed in the lab, he knows that she has carried out a measurement. Therefore, he ought to condition his predictions on the mixture of components in (8) rather than the full superposition. On this view the predictions of  $A$  and  $B$  for the  $\hat{O}$  measurement coincide: they both give probability of one–half to  $\hat{O} = +1$  despite the fact that their predictions are conditional on different quantum states.

**Reply** This argument is wrong–headed in the context of the information–theoretic approach, since it implies that a measurement induces a stochastic transition from a pure to a mixed state. This, however, is exactly what’s argued by collapse theories which aim at *constructing* a dynamical theory in which such transitions can be accounted for. To put matters differently, if option (b) is no option, then what is the difference between effective and genuine collapses?

**(iv) Option (a) is wrong.** Only the full quantum state in (8) is the right one for conditionalization (for both  $A$  and  $B$ ), because the  $\hat{O}$ –measurement involves interference between the two components of the state in (8).  $A$ ’s information about the outcome of the spin measurement becomes completely irrelevant due to the *objective* (observer-independent) features of the dynamics of the quantum state involved in the  $\hat{O}$ –measurement itself. In the information–theoretic approach one could even argue that this is the ‘flipped–side’ of the uncertainty relations: since the value of  $\hat{O}$  is known in advance with certainty,  $A$ ’s information about the spin outcome is unreliable, and this is manifested by the fact that  $A$ ’s ‘memory’ of the spin value (i. e., her record observable) and  $\hat{O}$  are maximally non–commuting. Moreover, as suggested by Bub (2005, Sec. 4), in the information–theoretic approach the emergence of classical information is explained (only) by decoherence. But, by construction, the  $\hat{O}$ –measurement requires *recoherence* of the components in (8). Therefore, whatever information these components carry ought to be disregarded (by both  $A$  and  $B$ ) in the face of the  $\hat{O}$ –measurement. Hence option (a) is no option, and the above inconsistency is resolved.

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Then,  $A$  and  $B$  differ in their predictions about the outcome of the  $\hat{O}$ –measurement. Why not just carry out the measurement and see whose prediction is right?

**Reply** This is the strongest argument one can hope for in defense of the Bayesian information–theoretic approach as well as Bub’s principle approach. But it relies on assumptions that are not explicitly stated in these approaches. Consider the claim that  $A$ ’s memory of her spin outcome is *unreliable* in the face of the  $\hat{O}$ –measurement. In so far as standard (operational) quantum mechanics goes, we are faced with a situation in which the measurement of spin on  $P$  is followed by a measurement of  $\hat{O}$  on  $P + M$ . Since  $\sigma_z \otimes \mathbf{1}$  and  $\hat{O}$  are (maximally) non–commuting, the statistics of their outcomes on consecutive measurements satisfies the uncertainty relations, so that the outcomes of the  $\hat{O}$ –measurement are only probabilistically determined by the outcome of the spin measurement (in accordance with the Born rule). That’s about all we can say in an operational black box treatment of measurements. Whether or not  $A$ ’s memories are reliable *during* the measurement of  $\hat{O}$  is a question that cannot be settled by a quantum theory of black boxes nor by the CBH constraints on information transfer. It cannot even be settled by appealing to the fact that perceptions and memories most plausibly need be modeled by systems that undergo environmental decoherence. This is why the information–theoretic approaches do not circumvent Bell’s (1990) objection that decoherence is not enough in order to make sense of quantum measurement. So the above argument requires additional laws (over and above the laws of quantum mechanics) about the dynamical behavior of  $A$ ’s memory during the interference involved in the  $\hat{O}$ –measurement.<sup>22</sup> But, strictly speaking, such laws are nothing but laws about the behavior of hidden variables, and so accepting point (iv) above would be tantamount to accepting that the information-theoretic approach is a hidden variables theory in disguise.

Before concluding this section, let us sketch two further objections to our thought experiment. It is sometimes claimed that our contraption above is, for some reason, excluded *as a matter of principle* by quantum mechanics. Although not explicitly stated as such in the literature, we have encountered two types of arguments to this effect which in slightly different ways bear on an alleged ‘impossibility of a God’s–eye view’ in quantum mechanics. These

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<sup>22</sup>In Bohm’s theory, for example,  $A$ ’s memory of the spin is perfectly reliable since the trajectories given by Bohm’s deterministic guidance equation cannot cross each other. By contrast, in modal interpretations where the dynamics of the extra values is stochastic,  $A$ ’s memory of the spin might flip during the  $\hat{O}$ –measurement. Anyway, on either theory the analysis of  $\hat{O}$ –type measurements is a straightforward physical analysis, and neither says that such measurements are *unphysical* or cannot be carried out, or what have you.

two folklore arguments go roughly as follows.

- (v) A single observer (say the observer  $A$  confined to the lab) cannot carry out both the spin measurement and the  $\hat{O}$ -measurement, since  $\hat{O}$  is an observable of  $P + A$ , and therefore measuring it by  $A$  entails some problematic form of *self-reference*.
- (vi)  $\hat{O}$  and  $A$ 's spin memories (as we said above) do not commute, and therefore no single observer can ever be in a position to know (with complete certainty) the values of both  $\sigma_z$  and  $\hat{O}$  (as manifested by the uncertainty relations). So if  $A$  knows the value of  $\sigma_z$  (as we assume) she cannot possibly know simultaneously also the value of  $\hat{O}$ .

On both objections quantum theory itself imposes some sort of physical constraints as to the identity of the observers who may carry out  $\hat{O}$ -type measurements. In particular, this is taken to mean that  $\hat{O}$ -type measurements are for some reason meaningless, or that our charge of the inconsistency of  $A$ 's predictions is somehow unphysical or cannot in principle be revealed by a single experiment, as it requires a God's-eye view which is unavailable to us.

As a response we only wish to say that both these arguments and various variants thereof are completely off the mark in the context of our thought experiment. First, the question of whether or not our thought experiment involves self-reference of any sort is *irrelevant*, since the issue boils down in its entirety (as we presented it above) to a straightforward question about the *predictions* of  $A$  as to the statistics of the outcomes of the  $\hat{O}$ -measurement—*no matter who carries out the measurement!* Second, as a matter of fact, our contraption above would involve no problematic form of self-reference even if we were to assume that the  $\hat{O}$ -measurement is to be carried out by  $A$  herself. Third, quantum mechanics itself imposes no physical constraints whatsoever on the identity of the observers who may carry out  $\hat{O}$ -type measurements. Fourth, our argument above leads to no sort of infinite regress nor does it require any form of a God's-eye view, as can be clearly seen from the above formulation of the thought experiment and the discussion that follows it.<sup>23</sup> By this we have established our thesis III above, namely that the information-theoretic approach is incomplete and nee be supplemented by further principles.

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<sup>23</sup>For a more extensive discussion of some of these issues we refer the reader to Albert (1983, 1990).



## 5 Conclusion: the Ancilla Argument

In this paper we have criticized the information–theoretic approach to quantum mechanics and Bub’s ‘principle’ reading of the CBH theorem. Agreed, the theorem remarkably demonstrates that certain salient features of quantum mechanics as we know it (by empirical observation) can be expressed very elegantly in information–theoretic terms. But it does not support any preference to the principle view of quantum theory over its constructive counterparts. Moreover (and unlike other constructive no collapse theories), our thought experiment clearly shows that the information–theoretic approach does not address major unresolved interpretational issues of quantum theory some of which await *empirical* resolution.<sup>24</sup>

More generally, the question raised by this paper boils down to the following. Do we know today whether quantum mechanics *as is* is here to stay, or is it more plausible to suspend judgment and wait until new empirical evidence comes in? Consider the following scenario. Suppose that crucial experiments that are capable of distinguishing between, say the GRW theory and environmentally induced decoherence were to come out (no kidding!) in accordance with the GRW predictions to a very good approximation.<sup>25</sup> Nevertheless, it is often argued by quantum–information theorists, the principle (information–theoretic) approach to quantum mechanics would remain *intact* for the following reason.

Suppose that an *open* system  $S$  is subjected to *perfect* decoherence, namely to interactions with some degrees of freedom in the environment  $E$ , such that the environment states become strictly orthogonal. Suppose further that we have no access whatsoever (as a matter of either physical fact or law) to these degrees of freedom. In this case, the GRW dynamics for the density operator of  $S$  would be indistinguishable from the dynamics of the *reduced* density operator of  $S$  obtained by evolving the composite quantum state of  $S + E$  *unitarily* and tracing over the inaccessible degrees of freedom of  $E$ . It turns out that this feature is mathematically quite general, because the GRW dynamics for the density operator is a completely positive linear map (see Nielsen and Chuang 2000, pp. 353–373; Simon, Buzek and Gisin 2001, especially fn. 14). From a physical point of view, this means that the GRW theory is empirically equivalent to a quantum mechanical theory with a uni-

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<sup>24</sup>See also Hagar 2003.

<sup>25</sup>For recent progress see Adler 2005, Adler *et al.* 2005, Bassi *et al.* 2005a. See also Hemmo and Shenker 2005 for experiments testing thermodynamical effects.

tary (and linear) dynamics of the quantum state defined on a *larger* Hilbert space. In other words, one could always introduce a new quantum mechanical *ancilla* field whose degrees of freedom are inaccessible to us, and cook up a unitary dynamics on the larger Hilbert space that would simulate the GRW dynamics on the reduced density operator. Therefore, experimental results that might seem to confirm GRW-like dynamics could always be *re-interpreted* as confirming quantum mechanical no collapse theories on larger Hilbert spaces. In particular, such a theory could always be made to satisfy the three CBH constraints, and thus save the principle information–theoretic approach.

In so far as information–theoretic approaches are concerned it seems to us that the above argument is quite premature. In the present state of quantum mechanics we are far from being able to pinpoint a principle theory that need be protected *come what may*. The ancilla field in the above argument has, by construction, no observable effects (see, e.g., Diosi 1989) and this amounts to introducing hidden variables (or more appropriately, a new ‘quantum ether’) into standard quantum mechanics, whose sole role is to save some disputable principles against (putative) empirical refutation. If we are willing to accept *ad hoc* such an argument in the context of non–relativistic quantum mechanics, why should we reject similar ‘ether’–like approaches in the context of relativity theory, or hidden variables theories in the context of elementary quantum mechanics? Such approaches are sweepingly rejected (by information theorists) mainly because their complex underlying structure doesn’t translate into new empirical predictions. Moreover, although the ancilla theory could always be made to satisfy the three CBH principles (in particular the NO BIT condition) on the larger Hilbert space, in so far as our experimental capacities are concerned (as imagined in our scenario above) unconditionally secure bit commitment would be possible via protocols that require Alice or Bob to access the ancilla field (which *ex hypothesis*, is inaccessible). So, the NO BIT principle as a constraint on the feasible flow of information in the above story becomes quite idle.

More generally, we accept that one *might* have good reasons to protect unitary quantum mechanics against what might seem as straightforward empirical refutation. From a theoretical point of view it might turn out that both collapse and hidden variables theories could not be made compatible with some fundamental physical principles which we cannot give up without giving up some significant chunk of contemporary theoretical physics (con-

servation of energy or Lorentz–covariance might be such examples).<sup>26</sup> In that case a protective argument of the kind suggested above might be understandable. But, in our view the present state of quantum mechanics doesn't warrant such an argument. This is mainly because quantum mechanics itself has quite deep foundational problems not only at its most basic level (e. g., the measurement problem), but also for example in its generalizations to both special and general relativity. In such circumstances we believe that the right epistemological stance is to suspend judgment and let alternative theories and the experimental confirmation thereof flourish.

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<sup>26</sup>We thank Itamar Pitowsky for conversations about this issue.

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