International Journal of Quantum Foundations **10** (2024) 26 – 55

Original Paper

A Note on a Possible Solution to the Measurement Problem

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Received: 6 December 2023 / Accepted: 16 December 2023 / Published: 31 December 2023

Abstract: This article is a sequel to a recently published article by the present author (*IJQF*, **9**, 4). That article seemed to go some way towards providing a physical explanation of the mysterious probability amplitude nature of quantum mechanics' ψ waves, and in that way towards a possible solution to the measurement problem of quantum mechanics. This article begins where the previous article finished. It puts forward a 'local', causally deterministic, additional variable model of a quantum system's transformation from the potentiality described by the ψ function into actuality. The model's key element is the deeper-level, periodic physical process (double transition\basic process) postulated in the previous article. The model specifies what the additional variables are and how they work—and the sense in which they are 'local'. It explains the ontology of the potentiality represented by the ψ function in terms of the underlying double transition\basic process. The model is time-reversal invariant, and encompasses both fermionic and bosonic systems. Because the model is explicitly retrocausal—the possibility of retrocausality already latent in the basic process—it readily evades the various 'no-go' theorems, such as Bell's theorem, usually taken to show the impossibility of a local hidden variable model that agrees with the predictions of quantum mechanics.

Keywords: Measurement problem, hidden variables, wave function collapse, retrocausation, locality, Einstein vs Bohr

1. Introduction

In a recent article [48], the present author proposed a novel answer to Bell's 1987 question of what it is that 'waves' in wave (quantum) mechanics [4]—a question to which quantum mechanics (QM) has no answer, and which it does not ask. The article postulated an underlying periodic physical process that all spin-half particles are taken to undergo in the 'shadow' of the Heisenberg uncertainty principle (HUP). The process—a periodic double transition process, or 'basic process', between states of positive and negative energy—is an extension and generalization of an early idea of Dirac's. It was argued in the article that the process can account for the waves and wave packets (linear superpositions) of the QM formalism, including in the spin-one case—elements of the mathematical formalism 'modelling' the underlying actual physical process. The new perspective seemed to provide insight into other aspects of QM as well, including its 'raising' and 'lowering' operators, the Schrödinger *Zitterbewegung*—and,

rather unexpectedly, into the quantum field-theoretical problem of why a finite particle mass and charge is always observed despite the potentially infinite field energy surrounding a particle.

It was shown how the proposed process seemed to go some way towards a physical explanation of the mysterious probability amplitude nature of QM's mathematical ψ waves (i.e. why the waves are associated with *probabilities*), and in that way towards a solution to the attendant measurement problem of QM—something not explained by Born's rule, which is just that: a rule. However, the proposal was not yet a solution to the measurement problem.

What was still lacking was an explanation of why measurements have determinate outcomes. Why is some *particular member* of a linear sum of possible measurement outcomes selected by a measurement? Why is that outcome selected in preference to some other possible result? This is known as the measurement problem.

This article begins where the previous article finished. It proposes a possible answer to the question of why measurements have determinate outcomes, the answer being directly connected with the underlying process proposed in the previous article. More specifically, this article puts forward a 'local', causally deterministic, additional variable model of a quantum system's transformation from the 'Heisenberg potentiality' represented by the ψ function, into actuality. The model specifies what the additional variables are and how they work—and the sense in which they are 'local'. It explains the ontology of the potentiality represented by the ψ function in terms of the proposed deeper-level physical process (the double transition\basic process). The model is time-reversal invariant, and encompasses both fermionic and bosonic systems, and applies to complete events. It does away entirely with what Bell described as QM's "shifty split of the world into 'system' and 'apparatus'" [6], p. 34.

Because the model is explicitly retrocausal (the possibility of retrocausality already latent in the underlying basic process; see Sect. 4), it readily evades the various 'no-go' theorems, such as Bell's theorem, usually taken to show the impossibility of a local hidden variable model that agrees with the predictions of QM. In fact, a retrocausal strategy seems to be a natural heuristic for tackling some of the puzzling aspects of quantum mechanics, as several authors have argued, e.g. Costa de Beauregard [13, 14]; Cramer [15]; Price [39]. Despite the potential advantages, retrocausation has not made it to the mainstream. That's partly because it seems so counterintuitive, but mainly because so far there is no generally accepted explanation of just how a (local) retrocausal theory could work.

This article attempts such an explanation. It is structured as follows. First, the measurement problem is briefly described (Sect. 2). It is followed (Sect. 3) by a recap of the 'basic process' that was introduced in the previous article [48]. Sect. 4 introduces advanced action and its copesmate, retrocausation. These preliminaries out of the way, the article then describes the proposed explanation of why measurements have determinate outcomes (Sections 5-7). The explanation includes a clear-cut answer to the question of the ontic state of a quantum object\system between measurements. Possible objections are noted and responded to. Sect. 8 is a brief comparison of the present proposal with Bohm's causal interpretation of QM. Some implications of the present theory and a prediction follow in Sect. 9.

2. The measurement problem: the transition from potentiality to actuality

Below is a simple illustration of the measurement problem in the context of the textbook account [20] of the spontaneous decay of an atomic excited state—for simplicity, the decay of the first excited state of the hydrogen atom to the ground state in the Schrödinger non-relativistic formalism. Even though the illustration is simple, the issues it raises are general, arising in all measurements, whether effected by nature or by an observation. The textbook illustration sets

things up nicely for the description of the presently proposed solution; we shall need to refer to it (the illustration) from time to time.

Take an electron bound to a hydrogen atom (H-atom), which a measurement has just found to be in the first excited state n_2 with the energy eigenvalue E_2, the state corresponding to the energy eigenfunction ψ_2. Call the atom 'atom A' or just 'A' for short and the excited state 'E_2'. The state of the electron can be approximately described as a stationary state in a central field of force. The probability of atom A remaining in this (quasi-) stationary state reduces exponentially with time, the state's mean lifetime being $\sim 10^{-8}$ s before its decay to the ground state n_1 with the energy eigenvalue E_1, along with the emission of a photon of energy $E_2 - E_1$. Call the ground state 'E_1'.

During the course of the decay, standard QM represents the (unobserved) electron's state as a linear combination, or superposition, of stationary states—non-relativistically, a superposition of the ground state and the first excited state. The decay is taken in quantum electrodynamics (QED) to be induced by perturbations by the zero-point fluctuations of the surrounding ground-state quantized electromagnetic field, or 'radiation field'. The field has a Hamiltonian function and can absorb energy, and is subject to Heisenberg uncertainty. The perturbation—a kind of resonance interaction between the atom in the initial state and vibrations of the appropriate frequency in the surrounding radiation field—induces the (quasi-) stationary first excited state into a linear combination (or superposition) of stationary states (here the ground state and the first excited state), expressible as a solution of the time-dependent Schrödinger equation. In one dimension, the combination may be written as follows:

$$\Psi(x,t) = c_1(t)\psi_1(x)e^{-iE_1t/\hbar} + c_2(t)\psi_2(x)e^{-iE_2t/\hbar}. \qquad (1)$$

The '(t)' in (1) is simply to remind that the expansion coefficients (or amplitudes) are functions of time. It is dropped for brevity in (2) and (3). The corresponding probability density function is

$$\Psi^*\Psi = [c_1^*\psi_1^*(x)e^{+iE_1t/\hbar} + c_2^*\psi_2^*(x)e^{+iE_2t/\hbar}][c_1\psi_1(x)e^{-iE_1t/\hbar} + c_2\psi_2(x)e^{-iE_2t/\hbar}]. \qquad (2)$$

The product $\Psi^*\Psi$ has four terms:

$$\Psi^*\Psi = c_1^*c_1\psi_1^*(x)\psi_1(x) + c_2^*c_2\psi_2^*(x)\psi_2(x) + c_2^*c_1\psi_2^*(x)\psi_1(x)e^{+i(E_2-E_1)t/\hbar} + c_1^*c_2\psi_1^*(x)\psi_2(x)e^{-i(E_2-E_1)t/\hbar}. \qquad (3)$$

The time dependences cancel in the first two terms of (3) but not in the last two (the cross terms) containing complex exponentials. The presence of the complex exponentials means that the atomic electron behaves as an oscillator with the angular (beat) frequency $\omega = (E_2 - E_1)/\hbar$, which works out at $\sim 10^{16}\,\mathrm{s}^{-1}$. The system's charge density oscillates in time between the two stationary states at this frequency. It is therefore capable of emitting or absorbing photons of the same frequency to or from an incident field, including the radiation field of QED, which is why, according to standard QM, an atomic excited state is not stable but decays over time. See [20]. The evolving values over time of the expansion coefficients c_2 and c_1 in the intermediate state (1) are proportional to the probability of a transition from E_2 to E_1 having occurred. The initial wave function in the superposition gradually gets weaker during the average lifetime of the excited state ($\sim 10^{-8}$) while the final wave function becomes correspondingly stronger, until it alone is present. However, the connection of the continuously changing wave function and probabilities to the observable event is only *statistical*; the transition can take place *at any instant* during the average life of the state, albeit with an ever-increasing probability over time that it has occurred.

Just what is it that determines the transition details in any particular case, such as the instant of transition, and why is some particular member of the linear combination selected by an appropriately quick measurement, rather than one of the others? What makes the transition happen at all, even given the presence of the perturbing background electromagnetic field of QED? According to QM, nothing save *pure chance*. QM remains intrinsically probabilistic. At the critical point in the field-theoretical explanatory story of the collapse or reduction of the linear combination, there is a gap in the explanation. That's just the point where the *deus ex machina* of pure probability enters and does the actual work, and effects the collapse. Similarly for upward transitions. Thus, as Bell put it [5], p. 201, "Either the wave-function, as given by the Schrödinger equation, is not everything, or it is not right". The linearly superposed intermediate state itself of course also remains physically uninterpreted.

There are also two related problems. It is not clear what a measurement *is*, or just when and where it occurs—where to place the dividing line, the 'von Neumann cut', between micro and macro systems. If the world is to be represented quantum-mechanically in terms of quantum waves undergoing unitary evolution, then, rather than collapsing, the wave function necessarily develops into a sum of parts that corresponds to incompatible *macroscopic* possibilities. A cut needs to be put in by hand somewhere in the chain of measurement to accord with the fact that macroscopic observables have determinate values. The latter failing is highlighted in the 'Schrödinger's cat paradox'. The second difficulty is that the reduction postulate seems to entail an absolute frame of reference—that of the measuring apparatus, making it internally inconsistent with the 'spirit of special relativity' [15, 37, 43].

This article will attempt to fill in the gaps in the above explanatory story. Since the key element of the proposed explanation is the basic process that was introduced and described in [48], that process is briefly described below.

3. Revisiting the basic process

In 1929 Dirac was struggling with a problem to do with the Klein-Nishima formula on Compton scattering in the context of what is now known as his hole theory of the positron. It turned out that nearly all the electron scattering came from the system's jumping into brief-lived intermediate states with negative (–ve) energy. Yet, given the exclusion principle and Dirac's own theory, it was absolutely forbidden for the electron to jump into states of –ve energy, no matter how briefly, since the postulated –ve energy electron sea was filled or almost filled. His solution, published in 1930 [17], was to postulate an intermediate 'double transition' process, in which a –ve energy sea electron jumps into a positive (+ve) energy state from the –ve energy sea, and a +ve energy electron jumps into the hole it left in the –ve energy sea, with an emission & absorption of radiation (equivalent to virtual pair-creation & annihilation).

Of course, nobody worries anymore about issues to do with Dirac's early theory of positrons as holes in a –ve energy sea of electrons. The main reason for that is not so much the theory's infinite energy and charge densities, requiring renormalization—their equivalents exist in all serious approaches to a realistic theory of particle physics, as Penrose points out [38]—but because the Dirac hole theory is not quite right. It is thought it cannot be applied to massive bosons, and it fails to account for the interaction of the electron with the vacuum (e.g. the Lamb shift). Dirac's theory is now replaced by the fields of quantum field theory (QFT) and the –ve energy solutions of Dirac's equation correspond, via charge conjugation, to the +ve energy solutions of a similar *positron* equation, and quantum theory contains no physically real –ve energy states.

But progress in physics is usually made by dropping assumptions, as David Bohm once remarked. The dropped assumption in the author's previous article (and in the present) was the

irrelevance of Dirac's 1930 hole picture of positrons to modern quantum theory and the interpretation of QM. The article took the modern picture of positrons (in which the –ve energy solutions of Dirac's 1928 equation of a free electron in an electromagnetic field refer physically to +ve energy positrons) and Dirac's hole picture of positrons (in which positrons are holes in a –ve energy sea of electrons), as equivalent and alternative descriptions of the same underlying reality. It was shown that the objections to the Dirac picture don't apply to the theory proposed in the article.

The previous article then extended Dirac's double transition process in a novel and far-reaching way. The process, which in Dirac's theory occurred only during certain interactions such as scattering, was postulated to be *periodic* and occurring all the time quite independently of scattering or other interactions—though it could result in them. The idea was to treat the periodic double transition process as a *fundamental underlying process* that every electron, and every other spin-half particle, is ceaselessly undergoing in the 'shadow' of HUP. Its frequency and period were readily derived from the uncertainty principle, being $\omega = 2E/\hbar$ and $\tau = \hbar/2E$ respectively. These worked out at $\sim 10^{21}\mathrm{s}^{-1}$ and $\sim 10^{-21}\mathrm{s}$ for a low-energy electron, where E is the electron's mass energy. (The more energetic the electron, the greater the frequency and shorter the period.)

The basic idea was this: In standard QM, HUP allows a fermion of electron mass energy to disappear from the world for the above period ($\sim 10^{-21}\mathrm{s}$) provided that it is replaced within the period. According to the present proposal, it *must* so disappear, and reappear, and keep on doing so forever at the above frequency in the absence of an interaction. The process—equivalent to periodic pair annihilation and creation—is unobservable, falling, as it does, within the uncertainties of the Heisenberg time-energy relation $\Delta t \cdot \Delta E \approx \hbar/2$. The article focused on the electron for simplicity, though the process was taken to apply to all fundamental spin-half particles.

The proposed underlying process (basic process) was schematically depicted as in Fig. 1.

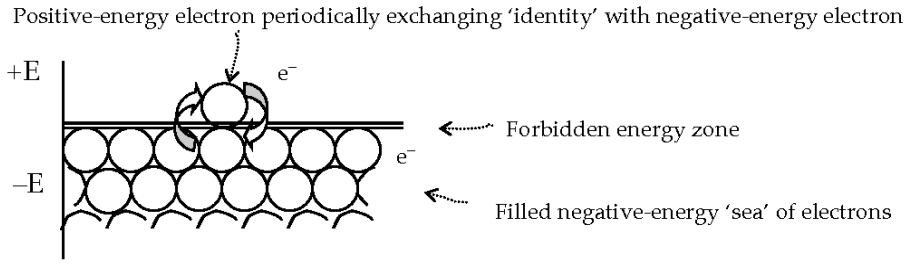

Fig. 1 An electron exchanging 'identity' with a –ve energy electron in the filled –ve energy 'sea', the exchange concealed by HUP

In an energy basis, the diagonal elements of the system's density matrix will be constant, as is necessary, because the total probability that the state is occupied by one or the other of the electrons will be constant. The reduced probability that one electron occupies a state is balanced by the increased probability that the other electron occupies that state, and the off-diagonal elements (the cross\interference terms which rotate) will be in accord with quantum theory, yielding the usual *Zitterbewegung* (*Zb*) or 'trembling' motion; the loss in oscillation amplitude as one electron leaves the state is balanced by the gain in amplitude as the other electron arrives.

The process reminds of the negative energy catastrophe that in 1928 seemed to be implied by the negative energy solutions of the Dirac equation, save that in the present picture the catastrophe is periodic, offset each time within the Heisenberg limit by its inverse: a *positive* energy 'catastrophe'. We shall find that, rather than taking the negative energy catastrophe as

something to be avoided, this article takes it to be the *key*—together with retrocausality, which is latent in it—to a possible solution of QM's interpretative problems.

In the absence of a physical interaction, the proposed process repeats without end with the frequency $(E-[-E])/\hbar \geq 1.6\times10^{21}\mathrm{s}^{-1}$ and period $\hbar/2E \leq 10^{-21}\mathrm{s}$. As the electron undergoes the process, it 'flashes' with virtual radiant energy during each up and down leg of the oscillation, the +ve energy electron emitting *pairs* of virtual photons on the way down the energy scale and its –ve energy counterpart absorbing pairs of virtual photons on the way up (and leaving a brief-lived hole in the –ve energy sea from which it emerged). Since the process is masked by HUP, one needs to think of the emission and absorption as occurring simultaneously.[1] Each emitted\absorbed photon is of an energy\frequency equal to a difference in energy\frequency between two adjoining energy levels or eigenstates of energy covered by the electron in its oscillation. The photons are paired because the electron traverses not only the +ve energy scale but also the –ve, resulting in a doubling-up of emitted & absorbed quanta. In the present idealized example (which was made physically realistic in the previous article), the emission and absorption is of a single pair of gamma photons, of frequency $\omega\approx10^{21}\mathrm{s}^{-1}$. Consequently the electron behaves as a simple harmonic oscillator, periodically 'flashing' in the shadow of HUP with virtual radiant energy of the above frequency.[2]

The proposed underlying process was found to be mathematically modelled in the general solution of Dirac's equation for a free electron by the +ve and –ve frequency rotations of the state vectors with the exponentials $e^{\pm iEt/\hbar}$. The solution looks like this:

$$\Psi(\mathbf{x},t) = \sum a_{+}e^{i(\mathbf{p}\cdot\mathbf{x}/\hbar - Et/\hbar)} + \sum a_{-}e^{-i(\mathbf{p}\cdot\mathbf{x}/\hbar - Et/\hbar)}. \tag{4}$$

One group of solutions in (4) corresponds to +ve frequencies and one group to –ve frequencies, the latter group associated with negative energies. The former solutions propagate forward in time, the latter backward. The former solutions are often called 'retarded' and the latter 'advanced'. In the associated probability distribution function there are cross terms connecting the +ve and –ve frequency states, giving rise to an oscillatory time dependence between the eigenstates belonging to each group of solutions. The cross terms oscillate (rotate) rapidly in time with the angular frequencies $\omega = 2mc^2/\hbar \approx 2\times10^{21}\mathrm{s}^{-1}$, where mc^2 is the rest mass energy [7], p. 38; [40], pp. 90-91, 280. The previous article took the frequency of rotation of the cross terms as modelling the proposed *actually occurring* underlying periodic double transition of the same frequency—an internal rotation—and the consequent periodic pair-annihilation & creation in the shadow of HUP (with emission and absorption of virtual quanta).

When the electron's momentum, and thus its energy, is well defined, the state may be approximated by a constituent solution of the general solution (4), i.e., by

$$\Psi(x,t) = a_{+}e^{i(p_x\cdot x/\hbar - Et/\hbar)} + a_{-}e^{-i(p_x\cdot x/\hbar - Et/\hbar)}, \tag{5}$$

which may be written simply as:

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[1] This is to do with the fact that when "two or more states are superposed, the order in which they occur is unimportant, so the superposition process is symmetric between the states that are superposed" [18].

[2] When an electron drops virtually into a negative energy state, its electric charge might be expected to be destroyed. The charge is not destroyed because the phase change is compensated for by the creation of a new 'gauge field' which preserves the conserved quantity in a different form. That new field is the virtual photon. The photon, in turn, is required for the electromagnetic interaction. So gauge symmetry not only conserves electric charge but also creates electric charge. As Zee puts it [51], p. 456, gauge symmetry doesn't relate two different physical states, but two descriptions of the same physical state.

$$\Psi(x,t) = a_{+}e^{i(k\cdot x - \omega t)} + a_{-}e^{-i(k\cdot x - \omega t)}. \quad (6)$$

Solution (5)\(6) represents the linear superposition of a retarded plane wave (a de Broglie wave), and its complex conjugate plane wave, the latter being a wave of –ve frequency. More specifically, the left term in the superposition is an electron wave function of four-momentum p and the right term is an advanced –ve energy\frequency electron wave function of four-momentum $-p$, reinterpretable as a +ve energy\frequency positron wave function.

For low energies and long durations we can pick either the +ve energy part of the solution or the –ve energy part, and discard the other. But when $\Delta t \approx \hbar/\Delta E \approx 10^{-21}$s (the period we are concerned with), that is no longer possible, and the solution represents both at once.

So even when there is *no physically real positron* in the vicinity, standard relativistic QM represents a single electron state as a superposition of electrons and positrons. Indeed, the mathematical Hilbert space contains states which are *inescapably* superpositions of +ve and –ve energy states [46], pp. 14, 24; physically, superpositions of electron and positron states. According to the present picture, the virtual positron member of the electron-positron superposition in (5)\(6) is in fact a simple consequence of the 'second' leg of the proposed periodic basic process—as the –ve energy sea electron jumps up to replace the +ve energy electron which jumped down, it momentarily leaves a hole in the sea (equivalent to a +ve energy positron), to be filled by the electron jumping down. Since the basic process is ceaselessly occurring in the shadow of HUP, the most general solution to the Dirac equation describes the electron as *always* accompanied by a virtual positron.

It was noted that the superposed plane waves (or wave functions) in solution (5)\(6) are each associated with an undetermined and uninterpreted phase factor, $e^{\pm iEt/\hbar}$, or $e^{\pm i\omega t}$, which continuously rotates an energy eigenvector to which it is applied through the angle ωt in a complex plane with the frequency $\omega = E/\hbar$. The rotations of the state vectors were taken to model mathematically in the QM formalism the proposed actual underlying basic process—the +ve frequency exponential $e^{i\omega t}$ responsible for the jump down with emission of energy, and the –ve frequency exponential $e^{-i\omega t}$ for the jump up with absorption of energy. This is much as in standard perturbation theory, where $e^{i\omega t}$ is responsible for the loss of energy and $e^{-i\omega t}$ for the gain; see [33]. In short, the proposed process was taken as the underlying reality and the rotations of the state vectors and the associated cross terms in the QM formalism its model.

The process was also taken to be the underlying physical basis of the mysterious 'Heisenberg potentiality', manifested in QM's linear superposition principle. It was argued that the constituent members of a linear superposition in the QM formalism simply model, directly or indirectly, the eigenstates of energy *actually physically traversed* by an electron or other spin-half particle, up and down the energy scale, as it undergoes the basic process, emitting & absorbing mutually interfering virtual quanta.[3] In this way, the system is enabled to be in many states simultaneously, as it were, under the cover of HUP, indeed, an infinity of states [48], pp. 203-205. Moreover, since the unobserved electron is transformed into electromagnetic radiation (emr) by the basic process, it is capable of self-interference like any wave, e.g. passing

[3] Of course, a representation of a system's state need not be in an energy basis. However, an arbitrary wave function, whatever its basis, can always be expanded, in principle, in terms of the eigenfunctions of the Hamiltonian, and the expanded wave function contains within itself the spectrum of all the possibilities that may be actualised through a measurement. As Penrose puts it, "Any self-respecting wavefunction, though it need not itself be an eigenstate of energy, ought to be expressible as a linear combination of eigenstates of energy…" [38], p. 613. See also [27], pp. 64-65. Kramers states that even the state of a free electron can be taken to be a superposition of stationary states—though whether with proper or improper eigenvalues may be left undecided [27], Ch. II, Sections 20-25.

through a slit system when unobserved,[4] and yet emerging at a detection screen such as a photographic plate as a single particle. The virtual quanta generated by the process were identified with the 'cloud' of virtual photons and other quanta dressing the electron\atom in QED. Massive bosons and composite systems were brought into the picture, as was photon 'waving'. It was shown how the picture avoids the earlier-mentioned objections to Dirac's original hole picture.

4. Advanced action; bringing in retrocausation

How might retrocausation and a possible solution to the measurement problem arise out of the proposed picture, indeed, be "latent" in it? Well, consider the *absorption*-leg of the above round-turn virtual process, in which the system, on its way up the energy scale, (re-)absorbs the photon pair it emitted on its way down the energy scale. It is known that the *absorption* of 'retarded', i.e. forward-in-time, emr is mathematically equivalent to the *emission of* 'advanced', i.e. backward-in-time, emr, the latter 180° phase rotated to the former (and conversely). See e.g. [45]. The 180° phase difference between the retarded and advanced fields at the source means that one is the negative of the other. Therefore we may think of the system in each completed round turn (i.e. both legs) of the basic process as *emitting*, within the shadow of HUP, a *pair* of retarded virtual photons\waves of emr *and*, simultaneously with that pair, a *pair* of *advanced* virtual photons\waves of emr (the latter emission mathematically equivalent to the absorption of a pair of retarded virtual photons). In short, instead of simultaneously emitting and absorbing pairs of (retarded) photons, we may equivalently and alternatively represent the system as simultaneously emitting pairs of both retarded *and* advanced photons.

Such emissions may be schematically depicted as in Fig. 2. The white circle represents the electron and the shadowed crescent attached to it is to remind of the electron's virtual positron counterpart of solution (5)\(6)—ever-present with the electron but unobservable owing to HUP.

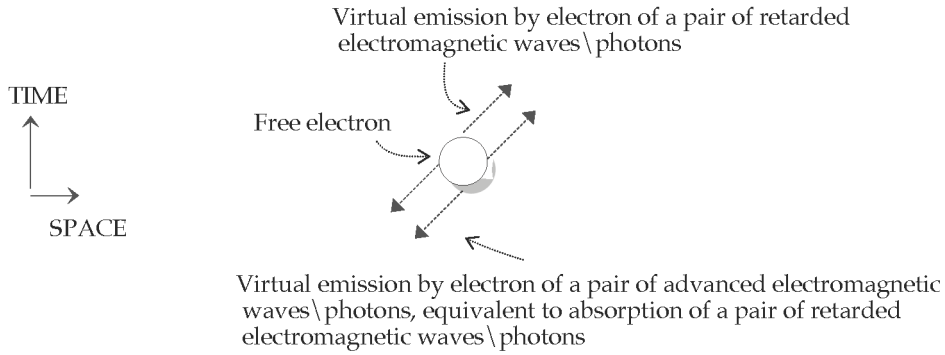

Fig. 2 Simultaneous emission of a pair of retarded & a pair of advanced photons in a single round-turn occurrence of the periodic double transition

Fig. 2 doesn't bring into the picture the electron's spacetime trajectory, nor its *Zb* oscillation that's always occurring as it emits and absorbs the resultant virtual radiation. Similarly, the virtual photons' spacetime 'trajectories' (diagonal arrows) are meant to indicate merely the fact of emission\absorption of such photons and not their propagation in any particular spatial direction. Both the retarded and advanced pairs of photons\waves co-exist for the period permitted by HUP, $\sim 10^{-21}$ s in the case of a low energy electron, before cancelling out.

So far, of course, this is not even retrocausation, let alone a solution to the measurement

[4] It's as if the electron were transformed into de Broglie waves propagating at the speed of light.

problem, but merely a verbal change of description. However, the fact that the periodic virtual emissions and absorptions attendant on a round-turn of the basic process can always be represented as the simultaneous *emission* of (i) a *pair* of *retarded* electromagnetic waves\photons *and* (ii) a *pair* of *advanced* electromagnetic waves\photons, will be of importance in the following sections when we come to describe the 'mechanics' of a system's transition from *potentia* to actuality. We shall find that it is only through the combination of advanced action and the *paired* nature of each such emission\absorption (the latter arising owing to the –ve energy solutions of the Dirac equation) that retrocausation is able to enter our explanatory picture.

5. The transition from Heisenberg's potentiality to actuality

In this section, a local and fully causal model of the 'spontaneous' decay of an atomic excited state is put forward. The precise sense of 'local' is specified. The proposed model is a *quantum direct-action absorber* theory. In direct-action absorber theories, as Pegg [35] points out: generally (i) there are no fields with independent degrees of freedom to quantize; only the particles are quantized, zero-point fluctuations of the vacuum having their source in the absorber, and (ii) there is or can be an intrinsic time-symmetry in the potentials. (See also [36].) The underlying 'basic process' described in Sections 3 & 4 above is a key component of the model. Even though the model is of a simple case of 'collapse' (the one described in Sect. 2), it is quite general, and seems applicable to all instances of reduction, at least in the electromagnetic case.

A consequence of the model, we shall find, is that an atomic electron is always in some *particular* physically real eigenstate of energy (in some particular determinate stationary state that would be revealed by a measurement) even when unobserved and when QM would describe the unobserved state as a *superposition* of stationary states (and when the present theory would describe the electron as also undergoing the proposed *virtual* oscillation or basic process).

As the electron interacts from time to time with its causal determinants (lying both in its past and future, we shall find), its state changes in a causally determinate way from being in one such determinate stationary state to another, completely independently of observation. We shall find that the electron's interaction with its past and future causal determinants is enabled by the underlying basic process. The details are below. They constitute a single extended argument.

5.1 A causally determinate model of a system's transition from Heisenberg's potentiality to actuality—showing how, when and where the transition occurs

Consider again the textbook account of wave function collapse in Sect. 2. Take the H-atom A which has just been found by a measurement to be in the E_2 state. According to the present proposal, at every instant, even immediately after the measurement (when the measurement found the atomic electron's *physical* state to be E_2), the electron is undergoing the postulated periodic 'basic process' in the shadow of HUP. This is the electron's ceaseless virtual double transition or 'oscillation' between E_2 and its negative, $-E_2$, with the angular frequency $\omega \approx (E_2 - [-E_2])/\hbar$ ($\approx 10^{21} \mathrm{s}^{-1}$). In the oscillation, the electron covers, *virtually*, all the stationary states of different energies, including E_2 and E_1.

As the system oscillates, it 'flashes' with unobservable paired bursts of virtual emr—paired emissions and absorptions of photons—one paired burst per each double transition, each such burst of total (angular) frequency $\omega \approx (E_2 - [-E_2])/\hbar$ and period $\tau = \hbar/2E_2$. Since the bursts are ceaselessly renewed as the electron continues to oscillate, they constitutes an ever-present *field* of virtual electromagnetic radiation about the electron. Each burst comprising the field may be 'sliced up' or Fourier-decomposed in any way that's consistent with Bohr's frequency or

quantization condition $\nu_{nm} = (E_n - E_m)/h$. Thus, it can be Fourier-decomposed into a linear superposition of quantized contributions from periodic sub-bursts or waves—component virtual photons—of various lesser frequencies\energies and correspondingly longer periods (lifetimes), including photons of frequencies proportional to the difference in the energies of the atomic energy levels covered by the jump, ω_{nm} $(= E_n - E_m)/\hbar$.

Suppose that E_n is E_2, as above. In that case a decomposition of the emitted burst of virtual emr has four terms, which may be linearly superposed:

$$\hbar\omega = (E_2 - E_1) + (E_1 - E_0) + (E_0 - [-E_1]) + (-E_1 - [-E_2]); \qquad (7)$$

equivalently: $\omega = \{(E_2 - E_1) + (E_1 - E_0) + (E_0 - [-E_1]) + (-E_1 - [-E_2])\}/\hbar$, where E_0 designates zero energy.

The terms sum to +ve frequency and energy, *double* the energy difference between E_2 and E_0. The summation represents four virtual photons: a pair of low frequency\energy photons and a pair of gamma photons, each of the latter equal to the electron's rest-mass energy. (For completeness, more terms would need to be added to take into account energy differences due to atomic fine structure.) The virtual photons are reabsorbed by the system within the period $\tau = \hbar/2E_2$. But for the period allowed by HUP, they all exist—one of the consequences being that the system is capable of exhibiting the property of self-interference when unobserved, since the created virtual emr\photons can mutually interfere.

A mathematically equivalent representation of the double transition process needn't explicitly bring into the picture the –ve energy sea at all (though it's always implicitly present). Simply represent the process as consisting of the virtual jumping down of an electron-positron *pair* from an E_2 state into a *zero* energy state (pair-annihilation), together with the simultaneous virtual jumping up of an electron-positron pair from a zero energy state into an E_2 state (pair-creation), with an attendant emission and absorption of paired bursts of emr.

The *pair's* round-turn jump (jump down and up) is just an alternative but equivalent (and convenient for the present purposes) way of representing the earlier-described unaccompanied or *non*-paired atomic electron's jump from E_2 to $-E_2$ and a –ve sea electron's simultaneous jump from $-E_2$ to E_2 to replace it—shown in the previous article to be equivalent to electron-positron annihilation and (re-)creation. There is no physically real positron. This 'paired' representation is the one we shall mostly use in what follows.

For simplicity, we can also ignore the rest mass energy and simply focus on the system's virtual oscillation between E_2 and E_1. That's because we can take any energy as our choice of the zero of potential energy [16, 23], and the emitted\absorbed field of virtual quanta is ever-present. So we may represent the electron-positron 'pair' as (virtually) oscillating in lockstep between the energy levels E_2 and E_1 with an appropriate lesser frequency, $\sim 10^{16}\ s^{-1}$, meaning that the electron's position relative to the atomic nucleus oscillates virtually with this frequency. In effect, by focusing on the oscillation between E_2 and E_1, we're defining the time t only as sharply as $\Delta t \approx 10^{-16}$ s, rather than $\Delta t \approx 10^{-21}$ s, where Δt is the residual uncertainty in the time.

During the period $\Delta t \approx 10^{16}\ s^{-1}$, the Heisenberg uncertainty in the system's energy ΔE would be ~10.2 eV, i.e. as large as the energy difference between the E_2 and E_1 energy levels. So no conservation principles are violated in the system's virtual oscillation between the two levels during such a period.

In the present simple case, the system behaves as a simple harmonic oscillator, emitting and absorbing paired virtual photons of frequency $(E_2 - E_1)/\hbar \approx 10^{16}\ s^{-1}$ in the shadow of HUP. This is the *same* frequency as standard QM's frequency of oscillation of an atomic electron's charge

density between its linearly combined states E_2 and E_1 in (3)—the latter oscillation in standard QM enabling the atom to interact with the radiation field and absorb and emit photons.

However, it needs to be emphasized that there are not *two* different oscillatory processes in play, namely (i) the above oscillation arising from the proposed double transition\basic process, and (ii) the mathematical oscillation of the off-diagonal elements of the density matrix connecting the two energy states, E_2 and E_1, as predicted by the time-dependent Schrödinger equation (with the consequence that the electron is an oscillating dipole). Only the former process is actually occurring—but it has the same effect as the latter. Both yield the same beat frequency. The latter process mathematically models the basic process in the ψ-function formalism of QM, but is not itself physically real.

What goes for one spin-half particle, goes for all. Every spin-half particle may be represented as always accompanied in the 'shadow' of HUP by its unobservable virtual antimatter counterpart particle—entirely consistent with the standard QM formalism, as is evident from (4), (5), (6)—the electron's enantiomorph doppelgänger positron being inextricably paired with it and undergoing the proposed basic process in lockstep with it. That also goes for the proton, i.e. its constituent quarks. In this sense, there always exists a hidden, very short-lived *anti*-world, ceaselessly flickering in and out of existence. Similarly for neutrinos.

As A's atomic electron jumps virtually from the first excited state E_2 to the ground state E_1 in the course of the proposed double transition process, say at the arbitrary instant t_0, it emits a virtual photon, of energy equal to the energy difference between E_2 and E_1. Simultaneously with A's jump, the virtual positron belonging to A's virtual counterpart antimatter atom does the same since the two are conjoined and their jumps phase-correlated.[5] Call the virtual counterpart atom 'A^*'.

Thus, owing to the jumps from E_2, the 'paired' system, call it $\boldsymbol{A}$, where '$\boldsymbol{A}$' refers to A and A^* collectively, emits at t_0 a *pair* of retarded virtual photons, each photon of angular frequency $\omega_{21} = (E_2 - E_1)/\hbar \approx 1.5 \times 10^{16}\ s^{-1}$. The photons propagate half their own wavelength (~10^{-8} m) before being reabsorbed by $\boldsymbol{A}$ at t_0, more or less at the instant of their emission, owing to the occurrence of the simultaneous inverse process, in which $\boldsymbol{A}$ jumps from E_1 to E_2. The round-turn process repeats periodically and generally remains virtual—behind the HUP veil. (Only the off-diagonal matrix elements rotate.) However, it need not remain virtual, provided the right boundary conditions happen to be in place to satisfy the conservation requirements for the process to become real. Here is how.

Suppose there happens to be another hydrogen atom, B, independent of A but lying on A's future light cone, no matter how far away. B of course also possesses a virtual antimatter counterpart B^*, paired with it and also undergoing the double transition process. For definiteness, we suppose that B's electron is known to be in the ground state E_1 at some arbitrary instant t_1, say at $t \cong 1$, just as A's electron was known to be in the excited state E_2 at the earlier instant t_0, say at $t \cong 0$. Again, $\Delta t_1 = \hbar/(E_2 - E_1)$, i.e. ~$10^{-16}$ s.

Even though B's electron's *physical* state at t_1 is the ground state E_1, the electron is at the same time ceaselessly virtually oscillating up and down the energy scale, between E_1 and E_2, completely independently of A. (For simplicity, we ignore the higher energy levels.) The same

[5] The *paired* (virtual) jumps are necessarily phase-correlated and occur in lockstep because they are simply an equivalent and alternative representation of a *single* (virtual) jump with two parts: (i) an atomic electron's jump from E_2 to E_1 with an emission of a photon and (ii) a *continuation* of that jump, from $-E_1$ to $-E_2$, with an emission of a photon. The latter part of the jump (from $-E_1$ to $-E_2$) is represented by A^*'s jump from E_2 to E_1. (As already stated, we're ignoring for simplicity the rest mass.)

goes for B's virtual positron counterpart B^*, oscillating in lockstep with B. Denote atom\atomic electron B by $\boldsymbol{B}$, where '$\boldsymbol{B}$' refers to both B and B^*. (For brevity, we shall use '$\boldsymbol{A}$' and '$\boldsymbol{B}$' to refer not just to the atoms $\boldsymbol{A}$ and $\boldsymbol{B}$ but also to their atomic electrons, as the situation may require.) We focus on the upward leg of $\boldsymbol{B}$'s round-turn virtual transition, i.e. the jump *up* the energy scale (in contrast to $\boldsymbol{A}$ where we focused on the downward leg). So at $t \cong 1$ (i.e. during Δt_1), $\boldsymbol{B}$'s electron is virtually jumping up the energy scale, *absorbing* energy, namely a pair of (retarded) virtual photons, of frequency $\omega_{21} \approx (E_2 - E_1)/\hbar \approx 1.5 \times 10^{16}\ s^{-1}$, period $\hbar/(E_2 - E_1) \approx 10^{-16}$ s and wavelength ~10^{-8} m.

How come atomic electron $\boldsymbol{B}$ is virtually jumping *up* the energy scale from the ground state at t_1 or, indeed, at any time? In the first instance, because of HUP, according to which $\Delta E \approx \hbar/\Delta t$. During the period Δt the system's energy is indeterminate not only down the energy scale but also up. This is not at all outside of quantum theory. Even in orthodox QM, in the presence of a suitable perturbation, "it is necessary to imagine that the system fluctuates simultaneously into all possible states, so that it covers all states simultaneously" [8], p. 452—that's to say, within the range defined by HUP, i.e. within the mean width, ΔE, of the wave packet [11]. The underlying *physical* reason for $\boldsymbol{B}$'s jumping up is described in Sect. 7. The jumping up should be taken as a heuristic postulate for now.

So at $t \cong 1$, atomic electron $\boldsymbol{B}$ is (virtually) jumping *up* the energy scale and *absorbing* a pair of (virtual) photons. We may depict the absorption as in Fig. 3. Fig. 3 also depicts $\boldsymbol{A}$'s earlier *emission*, at $t \cong 0$, of a pair of (virtual) photons associated with *its* oscillation, occurring completely independently of $\boldsymbol{B}$.

Fig. 3 and the rest of the figures in this section are schematic, in just the same way as Fig. 2. Moreover, for simplicity, the figures depict only one leg of the two-leg round-turn process, rather than both legs—in $\boldsymbol{B}$'s case the virtual absorption of photons, and in $\boldsymbol{A}$'s case the virtual emission of photons.

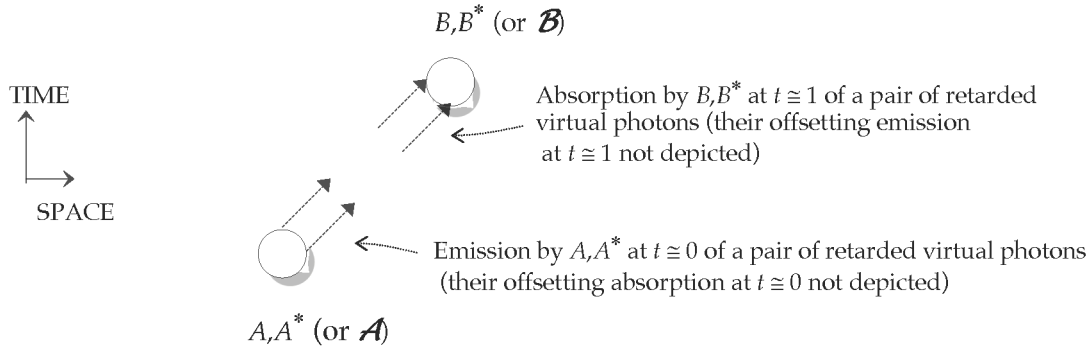

Fig. 3 Two independent atoms\atomic electrons $\boldsymbol{A}$ and $\boldsymbol{B}$ in opposite phases of the double transition process at different times, one ($\boldsymbol{A}$) emitting and the other ($\boldsymbol{B}$) absorbing virtual photons

The absorption by B (similarly, by B^*) of a retarded virtual photon is mathematically equivalent to the *emission* by B (or by B^*, or by both) of a 180° phase-rotated advanced virtual photon of the same energy (see Sect. 4). Likewise, the emission by A (similarly, by A^*), of a retarded virtual photon is equivalent to the *absorption* by it of a 180° phase-rotated advanced virtual photon of the same energy.

Thus, we may represent, completely equivalently, the independent paired virtual absorptions and emissions by $\boldsymbol{A}$ and $\boldsymbol{B}$ of Fig. 3 as in Fig. 4:

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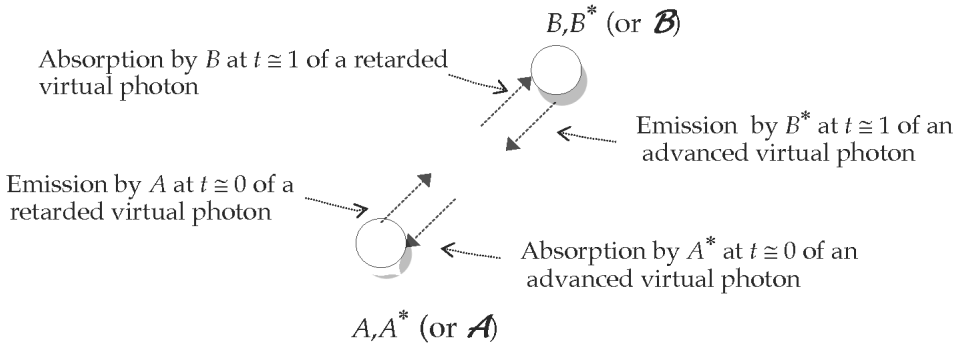

Fig. 4 An equivalent and alternative representation of Fig. 3 (one of several possible equivalent representations)

Similarly A^* and B^* themselves may be represented, equivalently and alternatively, as either (virtual) retarded positrons, or virtual –ve energy advanced electrons (i.e. backward-in-time or time-reversed electrons) [22].

During the average lifetime of the first excited atomic state of the hydrogen atom, ~10^{-8} s, the electron-positron 'pairs' belonging to both atoms ***A*** and ***B*** execute a great many such virtual oscillations between E_2 and E_1, of duration ~10^{-16} s each, simultaneously emitting and absorbing virtual photon pairs, emitting photons on the way down the energy scale and absorbing photons on the way up. The frequency of the emitted virtual emr is the same as the frequency of the beats that would be produced if the electron existed in a linear combination of both the E_2 and E_1 states, states whose characteristic frequencies are respectively $E_2/\hbar$ and $E_1/\hbar$—see (1) & (3).

Whichever their representation, though, the oscillations and emissions and absorptions remain *virtual*, being offset by their simultaneous inverses, else the conservation laws would be violated. ***A***'s and ***B***'s *real* energy states, i.e. states that can be found by a measurement, remain E_2 and E_1, respectively. (Mathematically, the diagonal matrix elements of the density matrix remain constant, even though the off-diagonal elements are rotating with the frequency $\omega \approx 10^{16} s^{-1}$.) Something additional would be required to transform one of the virtual emissions and absorptions into a physically real emission and absorption, indicating physically real transitions of state by ***A*** and ***B***.

Here is that additional 'something'. Suppose that, entirely by chance, the right boundary conditions for 'resonance' between atoms ***A*** and ***B*** exist, namely just the right phase relations, propagation vectors and oscillation frequencies between their virtually oscillating electrons and the virtual photons generated by the oscillation. Additionally, as already mentioned, ***B*** happens to be on ***A***'s future light cone. For resonance to occur, the frequency ω of the advanced incident photon emitted by ***B*** must be equal to the transition frequency ω_{nm} of the atomic electron ***A*** and appropriate phase relations must obtain between ***A***'s oscillation and the advanced photon's 'waving'. (Periodic quantities having the same frequency and waveform are said to be *in phase* if they reach corresponding values simultaneously; otherwise they are said to be *out of phase*.) The virtual emissions and absorptions need not be in such resonance even though the atoms have the same set of eigenvalues, since ***B*** and ***A*** are generally independent of each other, such that their relative phases, etc. are independent of each other.

However, *if* (and only if) the appropriate conditions for resonance exist, A^* absorbs at $t \cong 0$ the advanced photon emitted at $t \cong 1$ by the virtually energized B^*. Owing to the absorption, A^*'s so-far *virtual* jump down into the ground state E_1 becomes non-virtual, or physically real. E_1 rather than E_2 is now A^*'s new 'permanent' or long-lived physical state. (Concerning the jump *down* upon the absorption, that's explained by the 180° phase difference between retarded

and advanced fields at the source, meaning that one is the negative of the other.)

It's *as if* A^* had absorbed a *negative* energy *retarded* photon at $t \cong 0$ from the zero-point energy of empty space in its vicinity. That's much as in QED. The absorption of the advanced photon is represented in Fig. 5 by the lower diagonal arrow from $\boldsymbol{B}$ (i.e. from B^*) *entering* atom $\boldsymbol{A}$.

The chance absorption by A^* has the consequence that atomic electron A's virtual drop into the ground state E_1 is also rendered non-virtual or physically real. (Unlike $\boldsymbol{A}$ and $\boldsymbol{B}$, A^* and A are *not* independent of each other but necessarily phase-locked.) A has no choice but to emit a physically real photon, to be absorbed later by B (upper diagonal arrow). The completed interaction is depicted in Fig. 5.

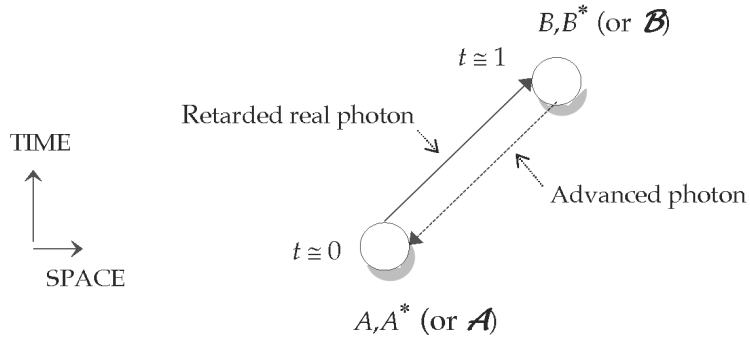

Fig. 5 A completed 'resonance' interaction of the present theory: the emission of a physically real photon by an atom and the photon's absorption by another atom. The interaction model is symmetric in time; see Sect. 6.

One might say, using the terminology of QFT, that part of A's field is 'switched off' (cf. [26], pp. 77-78, 97-98) owing to the advanced photon's absorption.[6] Such a switching off results in A's corresponding emitted virtual photon suddenly finding itself without its source. The now sourceless and companionless photon flies off as a *real* photon so as not to violate the conservation laws, to be absorbed later (at $t \cong 1$) by B, which jumps, non-virtually, into the E_2 energy level.

It should be evident that, since the advanced virtual photon that triggered the collapse is propagated backward in time, it can potentially act to cause transitions of state anywhere on its past light cone without violating the conservation principles. In this it differs from a *retarded virtual* photon which can only cover on its future light cone a spatial distance less than its own wavelength before being reabsorbed (in the present case $\sim 10^{-8}$ m)—the photon's lifetime before reabsorption being inversely proportional to its frequency ($\Delta t \propto 1/\nu$). In contrast, the advanced virtual photon's effective reach in causing transitions is limited only by the lifetime of retarded *real* photons. Since real photons are massless and don't decay, the effective reach is unlimited.

The advanced virtual photon emitted by B^* and absorbed by A^* has 'communicated' to A through its absorption not only the instant at which A must decay and emit a real photon, namely at $t \cong 0$, but also the details of the energy and propagation vector of the real photon that A must emit at that instant, such that the photon will be absorbed by B at $t \cong 1$. Thus, *A has a determinate energy at a determinate time*. Quite generally, this is how a system is enabled to possess a full complement of classical dynamical variables, albeit in a somewhat non-classical

[6] Some of the conditions constraining a successful absorption and physical transition of state seem to be summarized in the coupling constant $\alpha = \sim(1/137)$ for a real electron to emit a real photon. This article conjectures that a correlation of phase sufficiently sharp to enable a real interaction to take place occurs on average only once in ~137 advanced photon crossings of $\boldsymbol{A}$'s effective 'diameter'.

manner, the 'missing' or incompatible variables always being provided by future boundary conditions through the agency of advanced action, enabled by the underlying basic process.

Similarly with B. Upon absorbing the real photon from A at $t \cong 1$ (which necessarily arrived *in phase* with B's virtual oscillation), B jumps into an excited state.[7] The jump is non-virtual. The injection of just the right amount of real energy from A has made physically real one of B's virtual jumps up from E_1 to E_2 at $t \cong 1$ (the jump associated with B^*'s corresponding jump up and emission of the advanced photon to A^*).

A locally caused 'collapse' of a superposition (transition from Heisenberg's *potentia* to reality) has occurred in the case of both atoms, each at a determinate time, independently of a measurement or an observer. (Each transition is locally caused because there is no action at a distance even though it looks as if there were. See also Sect. 7.) This is how not only retrocausation but also a possible solution to the measurement problem is already latent in the underlying basic process.

It is convenient to think of the advanced photon emitted by B^* and absorbed by A^* as a successful 'probe'—the initial leg of a completed atemporal 'transaction', to borrow Cramer's terminology in his 'Transactional Interpretation' of quantum mechanics [15]. However, here the terms 'probe' and 'transaction' are shorthand for the elements of a completed causally deterministic, local and time-symmetric interaction, as contrasted with Cramer's intrinsically probabilistic, explicitly non-local and (subtly) time-asymmetric 'transaction', in which the emitter has a privileged role over the absorber.

The advanced probe need not have been successful in causing the emission of a real photon by $\boldsymbol{A}$. It could have failed to 'hit' (overlap with) $\boldsymbol{A}$ (i.e. with A^*), or failed to be absorbed by $\boldsymbol{A}$ even if the two did overlap. The vast majority do. It *happened* to be successful only because all the several necessary boundary conditions for the particular absorption that did occur happened to be satisfied.

5.2 Interpreting the zero-point radiation field of QED in terms of advanced 'probes'—photons from a system's future

Since every (physically real) electron that has ever existed or will exist undergoes the proposed ceaseless oscillation up and down the energy scale, acting as a collection of virtual oscillators, it follows that every atomic electron in the universe, both in our 'now' and in our distant future, is frenetically sending out cascades of such advanced probes into its past in every direction. The probes are of every allowed wave-number and frequency, including $\omega = (E_2 - E_1)/\hbar \approx 10^{16}\ s^{-1}$, as in the present simple illustration. There is thus a constant 'hail' of potentially resonant advanced probes converging along light cones upon every atom and every particle in the universe. The 'incident field' for a real downward transition is provided, not by the vacuum radiation field as in QED, but by the *advanced probes*; and the strength of the field depends on the *probe density*. It's as if the atom were in an applied electromagnetic field, from the system's future, with the resulting *real* or physical transition probabilities proportional to the energy density of the incident field, as in stimulated emission.[8]

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[7] It's as if the states of A and B were inextricably causally 'entangled' between $t \cong 0$ and $t \cong 1$, even though *timelike* separated. Such timelike entanglement is to be expected in absorber theory; see [36].

[8] What if there is no absorber in $\boldsymbol{B}$'s past in the right state of phase to absorb the advanced photon emitted by $\boldsymbol{B}$ (more specifically, by B^*)? In that case B^*'s emission of the advanced photon (equivalent to the *absorption* by B^* of a *retarded* photon) simply cancels out with the retarded photon emitted by B^* as the latter drops back to the ground

The probes result in a constant, fully causal, probability of decay per unit time—an exponential fall-off for the duration of the excited atomic state, just as is required. However, since there is no applied field, the system will *look* as if it were interacting with the zero-point radiation field of QED in an intrinsically probabilistic way, 'spontaneously' emitting radiation—which is why we never *see* the retrocausation at work.[9]

The above model seems to predict the correct 'spontaneous' emission rate of radiation from an atom in an excited state interacting with ground-state atoms in its future. Pegg [36] has calculated the rate in a case similar in the relevant details, i.e. a direct-action absorber theory and a fully absorbing universe, and found it to be in accord with QED. Pegg's direct-action absorber model is explicitly set up as an equivalent alternative to standard QM and remains intrinsically probabilistic, whereas the present model is causally deterministic, though of course not predictively deterministic.

The flux of probes generated by the double transition\basic process is the additional or 'hidden' variable involved in 'spontaneous' atomic decay. No probes, no atomic decay![10] The probes escape Bell's ban because, owing to their dependence on the future, they aren't quite the 'local' hidden variables in the sense of Bell's theorem [43, 49]. Bell's theorem, like the related GHZ theorems, depends on the assumption, known as the *independence assumption*, that quantum systems aren't correlated with the settings of measuring instruments *before* their interaction. Although this assumption might seem intuitively obvious macroscopically, there is no experiential warrant for it on the micro-scale, rather the opposite [39]. As Shimony put it [44], Bell's Theorem shows only that QM is incompatible with the conceptual framework within which Bell's Inequality was demonstrated. That framework includes a 'local causality' assumption, which presupposes a *one-way* causal 'arrow'. Bell's theorem didn't allow for the possibility of (local) *retro*-causal influences—that a QM system might be correlated with the settings of a measurement device *prior* to the system's interaction with the device. See Sect. 5.4 on how this loophole enables the present model to be untouched by Bell's theorem.

Since the observed average lifetime of the excited state E_2 is $\sim 10^{-8}$ s, it must take on average $\sim 10^8$ virtual downward transitions of A from E_2 to E_1, of duration $\sim 10^{-16}$ s each (the duration derived from HUP), offset by the same number of simultaneous upward virtual transitions, before such chance resonance occurs, enabling A's physically real transition from E_2 to E_1 and the emission of the real photon.

The model predicts that resonance can occur during the course of *any one* of the short-lived virtual transitions, at *any time* during the Schrödinger evolution of the state, even in its early part ($<< 10^{-8}$ s), with identical probability of occurrence per each virtual transition. Thus, the chance of it occurring during any particular one of the transitions (of duration $\sim 10^{-16}$ s) is one in 10^8. So the instant of the *physical* transition from E_2 to E_1 is a simple matter of statistics. When resonance does occur, it is quick, all over in $\sim 10^{-16}$ s—the transition period.[11] As has been

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state E_1 from its virtual excited state E_2. Consequently ***B***'s double transition up and down the energy scale remains entirely in the shadow of HUP, virtual and unobservable. No physically real photon is emitted or absorbed.

[9] The above 'mechanism' for the emission of radiation by an atom is strikingly reminiscent of the way a black hole emits Hawking radiation. In the black hole case, there is a negative-energy flux into the hole from the radiation field of the vacuum at a rate that compensates for the thermal radiation coming off it [32], pp. 484-485. Replace 'black hole' by 'atom' and 'thermal radiation' by 'electromagnetic radiation' and you have essentially the present mechanism, since the absorption of an advanced +ve energy photon is equivalent to the absorption of a retarded –ve energy photon, 'as if from the ambient vacuum'; see Sect. 5.1.

[10] An atom alone in space would not radiate, radiation requiring an atom's interaction with other atoms, just as Feynman proposed in his PhD thesis [21], an idea anticipated by H. Tetrode in 1922, and G. N. Lewis in 1930.

[11] Does *this* period ($\sim 10^{-16}$ s) represent an intrinsic indeterminacy in the state? It would seem not, since the underlying transition process is causally fully deterministic—the atomic electron gradually spiralling into the lower

shown, it results in ***A***'s decay and emission of a real photon of *determinate energy* at a *determinate time*.

However, even *after* the occurrence of the real transition pursuant to the above mechanism, in the absence of an observation, QM would continue to represent the state of ***A*** as the still evolving, *non-collapsed* superposition (1), i.e. $\Psi(x,t) = c_1(t)\psi_1(x)e^{-iE_1t/\hbar} + c_2(t)\psi_2(x)e^{-iE_2t/\hbar}$, for the entire remaining average lifetime of the state, with the (evolving) expansion coefficients c_2 and c_1 representing the ever-increasing *probability* over time of decay. The state of the atom is taken to be like the state of Schrödinger's cat—a superposition. Yet, objectively, immediately after the atom's absorption of the advanced photon, c_1 ought to be 1 and c_2 ought to be 0, and so the real state ought to be ψ_1 with the energy E_1, as a timely measurement would confirm.

5.3 The physical state of an unobserved quantum system: is QM complete?

The above model seems to show that standard QM *gives the wrong answer* concerning the physical state of the unobserved system. Contrary to standard QM, an observable of the system has a determinate value at every instant, even when the system's quantum-mechanically represented state is not an eigenstate of the observable, but rather a superposition of eigenstates. The eigenvalue-eigenstate rule has failed, reminiscent of certain modal interpretations of QM. It would seem that there is more to the physical state than is reflected in the wave function. If so, QM is incomplete.

The 'measurement' described above is of a quasi-stationary state, effected by nature. The proposed model is also applicable to measurements of stationary states and measurements by sentient beings and measurements of stationary states exhibiting no such time dependency. It would seem to describe the occurrence of quantum events generally, including composite events, each constituent of which is taken to have an advanced and a retarded component. The model readily lends itself, for example, to describing the spatial localization of an electron or a collection of atoms by a measurement, in accordance with Born's rule, as described in the previous article. And, owing to its advanced action component, it is a natural fit for explaining EPR without non-locality; see Sect. 5.4.

That is how the present account answers the question: 'what is the *state of an unmeasured quantum object*?'—whether the object be an atom or many atoms such as Schrödinger's cat. Take the cat. The above resonance 'mechanism' can be extended, in principle, to each and every (entangled) atom constituting the cat, with the result that each atom is physically always in some definite eigenstate of energy independently of an observer, even though *virtually* undergoing the presently proposed ceaseless transitions. The cat is always either alive or dead. (Inserting 'Wigner's friend' as an additional link in the experimental chain would add nothing of fundamental significance to the issue.) Because the theory is causally deterministic in just the right way, it is impervious to causal loop objections to backward causation theories such as Maudlin's objection [31] to Cramer's Transactional Interpretation of QM.[12]

The ontological status of the wave function is described below and in Sect. 7.

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energy level during this period under the cover of HUP, emitting virtual emr as it does so. So up to a point, it is like any classical process that takes a certain time from start to finish (though hidden from our ken).

[12] Even though the proposed model contains advanced action and causal loops, paradox is avoided because the model is in keeping with the convention for assessing counterfactual dependency, which says, 'hold fixed only that portion of the past which is accessible in principle', rather than the stronger mode which says, 'hold fixed the entire past'. The portion of the past that can coherently be taken to depend on our present actions, is the *inaccessible* past—that portion of the past which remains unobservable before we act to bring it about. Thus, the logical space for the possibility of symmetry between forward and backward causation lies entirely in the gap between the past and the accessible past [39], Ch. 7.

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5.4 If the world is causally deterministic, why is QM indeterministic? EPR and Bell's theorem

If observables have definite values at all times, as argued above, why does QM 'look' as if they didn't? How can that be reconciled with the contextuality theories which state the opposite?

In orthodox quantum theory, at most a well-chosen half of a complete set of variables can be assigned definite numerical variables, the other half—the values of the incompatible variables—remaining completely indeterminate [41], in the sense that such values do not even exist. Such a lack is built into the operator formalism of quantum mechanics. So to maintain that QM is a fully causal theory, it is necessary to show that a QM system does not lack the half of the required determinants that appear to be missing. Yet the system must at all times *look* as if it did lack them, requiring a theory of (seemingly) 'insufficient cause' to describe it, to borrow a phrase from Unruh [47]. For example, it must predict a violation of the Bell inequality, in contradistinction to classical mechanics. So a different type of causal account is required for describing fully *causal* hidden-variable QM systems than for describing classical deterministic systems, which are also fully causal. A new idea is needed. One might for instance argue, as e.g. Sciama suggested in 1958 [42] and as this article argues, that the missing half of the causal determinants refer to the system's future.

Such additional or 'hidden' variables were described in the preceding sub-sections. Since definite numerical values *are* available, at least in principle, for one half of the complete set of variables (i.e. those associated with our past), the additional variables must fix the values of the other half of the set—the complementary numerical values that are unavailable even in principle. In the preceding illustration of the decay of an excited atomic electron $\boldsymbol{A}$ from a known eigenstate of energy (i.e. a state for which the numerical value of the energy is known), the in-principle unavailable value was that of the *instant* of the decay.

As it turned out, the instant was determined by an advanced photon from $\boldsymbol{B}$ (more particularly, from B^*), absorbed by $\boldsymbol{A}$ (more particularly, by A^*), the absorption of the advanced photon determining the exact instant of $\boldsymbol{A}$'s decay (in effect, 'telling' $\boldsymbol{A}$ exactly when it must decay). In this way, QM systems would always seem to possess a full complement of causal determinants—one half of the set knowable in principle and the other half unknowable, or 'hidden'. The fact that one half of a system's set of causal determinants depends on the future explains why intrinsically probabilistic QM remains observationally adequate, even though, on the level of the hidden variables, the world is causally fully deterministic. Such a 'local' theory might also be described, with a nod to the Kochen-Specker theorem, as 'retrocausally contextual'.

Take EPR and Bell's theorem in the Bohm spin reformulation [8]. One of Bell's assumptions for the purposes of his proof was the EPR assumption that the two particles are separate entities each of which always possesses a definite spin component along every axis. That assumption is tantamount to requiring, as Bell himself put it much later, that each particle somehow carries in its own body a hidden 'program' or 'instruction set' correlated in advance with all possible detector settings, telling it how to behave upon encountering the detector. That is so because there is no communication between the source and the detector other than the particle itself. Unfortunately for that idea (and Bell's own realist leanings), Bell's theorem shows that local realist theories entailed correlations between distant singlet particles that were different from those predicted by QM. Any conceivable local realist theory had an upper limit to the correlations it could predict, or explain. Tighter correlations were a logical impossibility.

But that is not necessarily so if there can be communication between the source and the detector other than by the particle itself. The possibility of such communication arises in the

present proposal through the doubling-up of systems and advanced action. For example, we saw (Fig. 5) how atomic electron B's virtual positron counterpart B^* emitted an advanced photon which was absorbed by A^* and which communicated to A not only the instant at which A must decay and emit a real photon, namely at $t \cong 0$, but also the details of the energy and propagation vector of the real photon that A must emit at that instant, such that the photon will be absorbed by B at $t \cong 1$. Similarly in the EPR\Bell case, whether the experiment is of photon polarization correlation or spin correlation.

Take spin correlation. There is an electron-positron pair in a singlet state at the origin O, described in QM by a single wave function, which is the sum of the basic wave functions of the two particles. At $t = 0$ the particles move off in opposite directions towards a pair of Stern-Gerlach spin detectors with random magnet settings. How do the two manage to have their spins correlated so as to conform with Bell's prescription and the predictions of QM? According to the present proposal, there is no need for either member of the pair of particles to possess a *single* complete 'instruction set' covering every future measurement contingency—including all possible detector magnet settings for the future measurement of its (real) entangled twin's spin, which the particle must somehow take into account in 'knowing' what its own spin must be when measured. That's because the particles' virtual counterparts contribute to the maximal specification of their states (or instruction sets). Here is how.

When one of the real particles, say the electron member of an entangled electron-positron pair, arrives at a detector along one leg of the apparatus to have its spin measured, say the left detector, at $t = 1$, it is necessarily accompanied by its virtual positron counterpart, or enantiomorph 'shadow' (arising out of the basic process), which also arrives at the left detector at $t = 1$. Now, the virtual positron's arrival at the detector at $t = 1$ may be equivalently and alternatively described as the *departure* from the detector at $t = 1$ of an *advanced* virtual –ve energy *electron* towards the spacetime locus at the origin O, where it arrives at $t = 0$.[13] There it in effect 'informs' the real positron at the common origin of what the left leg detector setting is (completing the specification of the system's state at O), thereby correlating the physically real positron's future spin at the right detector with the left detector setting. And *vice versa*.

An objection is that Schrödinger's equation doesn't have advanced or –ve energy solutions, and therefore the advanced electron propagating towards the origin cannot be represented by a wave function which is a solution of the equation. The reply is that Schrödinger's equation is not physically correct, because it is non-relativistic. The required advanced wave is the –ve frequency plane wave in the general solution to the Dirac equation (5)\(6). It is the term on the right in the superposition—the complex conjugate of the +ve frequency plane wave term on the left. The –ve frequency\energy term is an *advanced wave function*. Moreover, as Cramer has pointed out [15], when a suitable relativistic equation, such as the Dirac equation, is reduced to

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[13] Superficially, this idea is similar to the so-called 'two-state vector formalism' of QM, according to which an explanation of EPR required *two* wave functions between the detector and the origin, one propagating forward in time from the origin to a detector and the other backward in time from that detector to the origin, to be able to provide a complete specification of a quantum system's state. See e.g. [1, 2]. Such a formalism has not become mainstream, even though, as Penrose notes [37], p. 390, it enabled a "completely objective description of the state in EPR situations which can be represented in space-time terms consistently with the spirit of Einstein's relativity". Perhaps one reason is that the formalism's emphasis is on its operational elements rather than on any ontological prescriptions, including how to understand causality [24]. This may be contrasted with the present proposal, in which the underlying double transition\basic process provides both the ontological prescription and a (possible) causally expressed solution to the measurement problem. Superficially similar, too, are Costa de Beauregard's 1953 and subsequent attempts to explain EPR by means of a kind of zig-zag in spacetime by successive advanced and retarded waves [13, 14]. These attempts also focused on the operational elements; see [14], p. 934, and put forward no acceptable solution to the measurement problem.

the Schrödinger equation by taking its non-relativistic limit, two equations emerge: Schrödinger's equation and another equation,

$$-\left(\hbar^2 / 2m\right)\nabla^2\Psi = -i\hbar\left(\partial\Psi / \partial t\right)$$

where m is the mass of the actual physical particle. This is the *complex conjugate*, or the time reverse, of the Schrödinger equation. It is of the form of the Schrödinger equation but has only advanced solutions and –ve energy eigenvalues. The advanced wave, modelling the backward-in-time virtual electron, is a solution of this equation, just as the retarded wave (1), modelling the real electron, is a solution of the more familiar Schrödinger equation. Both are equally valid solutions of the dynamics underlying the Schrödinger equation. Whichever the representation, the present proposal takes the advanced wave as modelling the actual physical state of the virtual –ve energy electron which propagates backward in time, as in the above spin correlation illustration.

It should be evident, even from these few remarks, that what Bell ruled out as untenable is by no means untenable, given the present model. The key is the model's doubling-up of states and the ensuing additional variables located in the future of systems.

This option is unavailable in orthodox QM since it contains no additional (or 'hidden') variables and takes the wave function, effectively stripped of –ve energy solutions, to be a complete description of the state. So QM is forced to represent all the subtleties and consequences of an actual underlying physical state of affairs that *does* contain additional variables and –ve energy states and in which there is no dynamical collapse, by a model that *doesn't* contain additional variables. The same applies to the contextuality theorems. Hence the necessity in (standard) QM of the collapse postulate. Hence also the counterintuitive quantum-theoretical conception of 'state', represented by the wave function. That is the origin of the measurement problem.

Maudlin writes [30] that a viable solution to the measurement problem would require an account of two things: (i) the underlying nature, or ontology, of the potentiality represented by the wave function; and (ii) the dynamics of the 'collapse' of the wave function (actualisation of the potentiality), either by a collapse theory or an alternative theory that need involve no dynamical collapse, such as an additional variables theory. If the latter, one must specify what the additional variables are and what laws govern them. It seems to this author that such an account has now been put forward.

(i) The ontology of the potentiality represented by the wave function is given by the proposed double transition\basic process that the particle undergoes in the shadow of HUP. That process is taken as the underlying reality, the mathematical wave functions with their phase factors simply modelling the process. In particular, a QM linear superposition models, directly or indirectly, the eigenstates of energy physically traversed by an electron or other spin-half particle, up and down the energy scale under the cover of HUP, as it undergoes the basic process—the process transforming the particle into potentially self-interfering virtual quanta and back again. The QM formalism effectively models this process through the rotation of the off-diagonal elements of the density matrix, which rotate with the frequency of the proposed process (the diagonal matrix elements remaining constant).

(ii) The laws that govern the additional variables are exhibited in the present theory's retrocausal picture of the transformation of the potentiality into actuality; in particular, by its model of the 'spontaneous' decay of an excited atomic state (Sections 5-6). The model, arrived at through an investigation into the meaning of the wave function, shows *how, when and where* the decay occurs. The 'how' is through the causal action of additional variables lying in the atom's future, the additional variables arising out of the basic process, their

causal action being enabled by the process. The 'when' is the instant of the atom's absorption of an advanced photon, in the proper time of the atom. At that instant, a measurement, if one were made, would *find* the atom in the new state. The 'where' is at the atom itself; no hand-inserted 'von Neumann cut' in the chain of measurement is needed.

The ontology of the wave function and the 'laws' that govern the additional variables are further investigated in Sect. 7.

6. Time-reversal invariance of the proposed model

The above model of 'spontaneous' atomic decay and emission\absorption of light is time-reversal invariant and entirely consistent with the 'spirit of special relativity' (cf. [37]), as one would expect since it is causally deterministic. An equivalent, probability-conserving description of the proposed interaction process depicted in Fig. 5 can be given by interchanging 'start' and 'finish' (i.e. $t \cong 0$ and $t \cong 1$), and the labels 'retarded' and 'advanced'. The emission of a physically real retarded photon by ***A*** and its later absorption by ***B*** occurring in our conventional direction-of-time frame is, in a time-reversed frame, the emission of a physically real retarded photon by ***B*** and its later absorption by ***A***. So in a time-reversed frame, ***B*** absorbs an advanced photon from ***A*** at $t \cong 0$ and thereupon emits a retarded real photon which is later absorbed by ***A***, at $t \cong 1$.

Owing to the interchange of the labels 'retarded' and 'advanced' of the two 'legs' of the completed interaction, the emitter of the retarded (and physically real) photon in the time-reversed frame is not B but B^* (right-hand leg of Fig. 5). That's the *advanced* leg of the interaction in our temporal frame but now the retarded leg in the time-reversed frame. By the same token, the emitter of the advanced photon in the time-reversed frame is A (left-hand leg of Fig. 5); that's the *retarded* leg in our temporal frame but now the advanced leg in the time-reversed frame. The designations 'electron' and 'positron' also swap over.

Despite the interchange, there is no overall change even though the radiative arrow of time has reversed direction. Owing to the one-to-one mapping of all the elements of the interaction and the fact that the sign of the charge is conventional, the time-reversed world would look unchanged.[14]

The next section will attempt to place the proposed model of wave function collapse within a larger context that potentially has additional implications for the meaning of QM.

7. The ontic status of the wave function; conjugate dual 'worlds'

It was noted in Sect. 5.4 that the world seems to operate on the basis of 'insufficient cause'. The quantum-theoretical operator formalism, in its alternative position-space or momentum-space representations (or a mix of the two), ensures that QM always lacks exactly one half of the total data required for arbitrarily accurate predictions, since the data relates to incompatible

[14] There has been recent discussion about whether QM would require retrocausality for it to be time-symmetric [28, 29]. That discussion concerned the state of a photon between rotated polarizers\polarizing beam-splitters. Is the photon's polarization when *between* the filters aligned with the last (say, *vertically* polarizing) filter it passed through or with the future (say, *diagonally* polarizing) filter it is yet to encounter—vertical and diagonal polarizations being incompatible variables? The present theory would say that there are *two* photons between the filters, one retarded and one advanced, each aligned with the last filter it passed—the retarded photon with the vertical filter and the advanced photon with the diagonal filter. Upon time reversal, the designations 'retarded', 'advanced', etc. would swap over, just as in the atomic decay example of Sect. 5. The system would look the same. Lack of space prevents providing the details here.

measurements. As Schrödinger wrote [41],[15]

> … at most a well-chosen *half* of a complete set of variables can be assigned definite numerical values… The other half [i.e. the incompatible half] then remains completely indeterminate.

In our model an advanced photon from the system's future provided the missing half of the complete set of data for a fully causal account of the decay of the excited atomic state from E_2 to E_1. The system did not lack 'sufficient cause'. According to standard QM, the in-principle unavailable data was the *instant* of the decay (the *incompatible* or non-commuting variable when the energy is known). But in our model that instant was determined (Fig. 5) by an advanced photon from ***B*** (more particularly, from B^*), absorbed by ***A*** (more particularly, by A^*), which, in effect, 'told' ***A*** exactly when it must decay. So the incompatible variable had a determinate value after all. If so in this case, then so in every case. QM systems always possess a full complement of causal determinants—one half of the set knowable in principle and the other half unknowable, or 'hidden'—but existing nonetheless.

What would be the ontological implications of such a picture, for the ψ–ontic\ ψ–epistemic debate concerning the reality of the wave function, and more generally?

The picture must be a consequence of some more general theory that encompasses the presently proposed model and the half of the determining conditions lying in systems' future. What might be the specifics of such a theory? We now enter deep waters and proceed with all due regard for fallibility. The present state of the world is generally taken to be the result of *past* boundary conditions (BCs)—how things started out. But according to the present picture, exactly half of the determining conditions for arbitrarily accurate predictions—the complementary half—lie in the future of systems. *Both* exist and act on a system simultaneously. Since so, consistency would seem to require an *additional* set of BCs, associated with the future half of the determining conditions. Those BCs must lie in the future of systems. We may equally take those *future* BCs as the beginning, or 'how things started out'. That's because there is nothing *privileged* about either direction of time in the present model (Sect. 6) or about either member of a pair of QM's canonically conjugate variables, such as position and momentum, or time and energy\frequency. *Which* member of the pair happens to be associated with the past BCs and which with the future BCs simply depends on the measurement we choose to perform. But that gives *two* equally good beginnings (or initial conditions)—one in our past and one in our future. There is nothing to choose between them, and both act on a system simultaneously. Consistency requires that we choose both.

So, given that exactly half of the determining conditions for arbitrarily accurate predictions lie in the future of systems, as described in the preceding sections, it seems inescapable that a time-reversed world to our world on the quantum level actually exists, alongside our world—our world's dual, complementing it. Everything that happens, happens in *both* directions of time on the quantum level.

Each world, in the absence of its dual, would lack exactly one half—a mutually complementary half—of the causal determinants for arbitrarily accurate predictions. However, in the present model, the numerical values of the other half of the set are always determined by the world's opposite-time dual, conveyed from the one world to the other through the double transition process\basic process and advanced action, in the way described below.

The two opposite-time worlds are complementary aspects of a 'larger' or 'whole' world—a 'block-time' world, perhaps a closed hypersurface in spacetime [50]—in which there is no

[15] Eddington, too, noted in 1935 that "what is lacking to secure a complete and certain prediction of the whole future is always just *half* of the total data that would be needed" [19], p. 98.

objective division between past, present and future. One world's past BCs are the other world's future BCs, and *vice versa*. Together, the two possess all the usual canonically conjugate observables of classical mechanics, such as a determinate same-axis position and momentum. The two worlds—or two equally good groups of frames of reference (the individual frames connected by Lorentz transformations)—are interdependent, inextricably entwined and in ceaseless interaction on the quantum level, through the basic process and advanced action.

Even though the conjugate world's time is reversed to that of our world, identical physical processes to those of our world necessarily occur in it. Just as our world's 'now', or present, looks as if it is shaped solely by its *past,* 'effect' always following 'cause', so also the conjugate world's present looks as if it is shaped solely by *its* past—even though that past lies in our world's future. In conjugate-world (proper-time) frames of reference, too, entropy always increases, broken teacups remain broken, people grow older, not younger, remember the past, not the future… Conjugate world physicists would write Schrödinger's equation just as we do (though our-world physicists would maintain it is the complex conjugate of our Schrödinger's equation).

In the conjugate world, just like in our world, electrons undergo the double transition\basic process, periodically jumping down the energy scale in the shadow of HUP in search of (always elusive) equilibrium, while simultaneously –ve energy sea electrons jump up in *their* search for equilibrium. Similarly for all spin-half particles. The double transition process in the conjugate world is to be taken as *actually occurring* (albeit behind the scenes), just as it is actually occurring (behind the scenes) in our own world.

Represented from the vantage point of our *own* world, though, the conjugate-world real electron's jumping *down* the energy scale to a state of lower potential energy, with an emission of emr, equates to the jumping *up* the energy scale of a –ve energy sea electron in our world to a state of higher potential energy, with an absorption of emr. Owing to the reversal of the sign of time between the two worlds (equivalently and alternatively, of the sign of energy), the jumping down in the conjugate world with an emission of energy, manifests itself in our world as a (virtual) jumping *up* with an *absorption* of energy (equivalent to the *emission* of advanced energy as in Fig. 4 by B^*). Bear in mind that the worlds are not independent of each other but constitute a single, interacting, more complex world—a world which is neither entirely classical nor conventional quantum. By the same token, our real electron's jumping down manifests itself in the conjugate world as a jumping up of a –ve energy sea electron. Our world's pair creation is the conjugate world's pair annihilation, and *vice versa*. Let us dub this picture the *dual-world* theory.

It is the more complete answer to the question posed in Sect. 5.1, *viz*: how come atomic electron B^* is (virtually) jumping up the energy scale? Because of HUP, was the short answer. An underlying *physical* reason for the jumping up was also promised. It turns out that that the physical reason for B^*'s virtual jumping up is the *same* as for A^*'s virtual jumping down! Systems tend to seek states of lowest potential energy. Our world's dual is a world of matter. In any frame in it, just as in any frame in our world, electrons are undergoing the proposed basic process and there is a constant 'hail' of advanced probes\photons descending from the future along light cones upon every atom and every particle in that world, owing to which excited atomic electrons are enabled to decay, seemingly spontaneously, emitting physically real photons.

For anything to *happen*, identical processes must occur in both worlds. Take the emission of the (retarded) real photon by A and its absorption by B (left leg of Fig. 5). It was able to occur *only* because there was a matching emission of a (retarded) *real* photon and its absorption in the time-reversed conjugate world. In our world's temporal frame, this latter (retarded) real emission

and absorption 'looks' like the emission of an *advanced* photon by B^* and its absorption by A^* (right leg of Fig. 5), i.e. the hidden causal determinant of the instant of the real emission by A in our frame. Similarly for the emission of the real photon in the time-reversed conjugate world. It occurred only because B's absorption of the real photon from A (upper left leg of Fig. 5) is in that temporal frame the absorption of an *advanced* photon from A, i.e. the causal determinant in that frame of a *real* photon's emission from B^* to A^* (the right leg of Fig. 5).

It means that the system always 'knows' what it must do (while managing to look as if it never knew quite what to do). It is this 'bootstrap' interaction of the conjugate worlds (which, in effect, the mathematical quantum wave function attempts to model) that results in the familiar observed phenomena in our world. In its absence nothing could happen.

The interaction of the dual worlds is the underlying physical explanation of why, in the standard QM formalism, a system undergoing a transition between two states always has a 'foot' in each of the two states, the initial state and the final state, covering both at once, as is evident in (1). *Mathematically*, having a foot in each of the two states is required to preserve time-symmetry, since the matrix element for a process and its inverse are related by complex conjugation. Take radiative transitions. The matrix element that governs the rates of transitions depends symmetrically on the wave function of both the initial state and final state. Typically it is of the form

$$\langle \text{final state} | \text{operator} | \text{initial state} \rangle .$$

It means that the process of transition is indivisible and the system in transition must be thought of as covering both states at once: the transitional state is a linear superposition of the initial and final states. This is a peculiar and distinctive feature of the transition from an initial state of a quantum system to its final state. See [8, 33].

Physically, having a foot in each of the two states (in the mathematical formalism) is required because of the co-existence of the conjugate dual worlds—each the time-reverse of the other, the two in constant interaction, each providing the necessary boundary conditions for the other's existence, together constituting the whole world: an atemporal 'block-time universe'. Hence also the internal structure of Born's rule $|c_n|^2$: multiply the wave function by its complex conjugate, i.e. essentially by its time-reverse. Hence also the necessity for an equation with both +ve and –ve energy solutions, such as the Dirac equation.

It seems to follow that QM is the way it is because of *cosmology*. Each of the conjugate dual worlds carries exactly half (a mutually complementary half) of the causal determinants, and each such world is the way it is because of its initial conditions—or how it 'started out'. But since the two are just paired constituents of an atemporal block-time world, the arrangement of their initial conditions (such that the initial BCs of the one world are the final BC's of its conjugate dual, and *vice versa*) is necessarily due to the cosmological structure of the block-time world.

The interaction of the two worlds provides a new take on the famous Einstein-Bohr debate about the nature of quantum reality, and the ontic status of the wave function. Bohr maintained that there were no additional, or 'hidden', variables—and he was right: there *aren't* any, not in our world, the world accessible to us. In our world, the wave function represents all there is. Einstein maintained that there had to be additional variables (even though he accepted the correctness of the QM formalism)—and he was right: there *are*, but they are inaccessible to us, being in our world's dual. So it turns out that both antagonists were right, but in an unexpected way. However, Einstein was more right than Bohr, because it turns out that the two worlds *interact*, each world supplying the missing additional variables to the other on the quantum scale—with the consequence that the wave function seems to be 'epistemic' after all, simply

representing our state of incomplete knowledge of both the dual worlds.[16]

8. Bohm's causal interpretation of QM: a potted comparison with the dual-world theory

There is a handful of what might be called 'mainstream' alternatives to the standard interpretation of QM which either propose solutions to the measurement problem or in which the problem is taken not to arise. How does the present proposal compare with them? This article has argued that the measurement problem arises because exactly one half of the causal determinants of systems lie in their future. A corollary of this view is that any theory purporting to solve the measurement problem but which isn't explicitly built around such an understanding is likely to generate its own complications and seem forced, even *ad hoc*, because it won't be engaging directly with the source of the problem.

Take Bohm's theory (BT), also known as the 'causal interpretation' [9, 10] (and later as the 'ontological interpretation'). We take it as our point of comparison because in certain respects it is reminiscent of the presently proposed 'dual-world' theory: (i) like the dual-world theory, BT has particles and the particles always have determinate trajectories, at least in configuration space; (ii) like the dual-world theory, it is a hidden variable theory—in BT's case, 'hidden' in the sense that the particles are acted on not only by the usual potential, but also by an additional (or hidden) *quantum potential* which guides the particles; (iii) in both theories, systems can have definite observable properties even when the quantum state is not an eigenstate of the associated operators; (iv) neither theory contains an observation-generated dynamical collapse of the wave function; and (v) (in some versions of BT) the ψ-field is in a state of very rapid random and chaotic fluctuation, arising from a deeper, sub-quantum level, somewhat reminiscent of the dual-world theory's underlying basic process. The sub-quantum fluctuation results in an additional layer of hidden variables governing the positions of particles. So, in Bohm's theory "[an electron] has a position, a momentum, a wave field ψ, and sub-quantum fluctuations, all of which combine to determine the detailed behaviour of each individual system with the passage of time" [10], p. 79.

Despite the similarities, BT and the present dual-world proposal are very different theories. That's because BT doesn't have at its disposal the half of the causal determinants lying in systems' future, nor the 'basic process' which governs their interactions with systems.

In BT, the quantum potential is responsible for all the puzzling aspects of QM, just as in the dual-world theory the future half of a system's causal determinants together with the basic process is responsible for all the puzzling aspects (at least in principle). Bohm's quantum potential is based on de Broglie's notion of a pilot wave that governs a particle's motion. If one just puts out of mind the potential's curious holistic properties, one has a nice deterministic theory in which particles always move along well-defined paths and there are no wave function collapses nor any of the usual quantum weirdness. Metaphysical arguments about the measurement problem, Heisenberg potentialities and actualities and irreducible probabilities no

[16] In a world containing no additional variables (no dual worlds), there would be a strong motivation to adopt a ψ-ontic view of the wave function. One could then attempt to source the Born probabilities and wave function collapse to something in the wave function itself, because, as Gao puts it, "even when assuming the ψ-ontic view, the ontological meaning of the wave function also has implications for solving the measurement problem" [25], p. 167. In particular, Gao argues that the wave function could refer to the random discontinuous motion (RDM) of particles, wave function collapse somehow originating from the RDM. Now, the (general) *Zb* derived in the present author's previous article from the basic process, seems consistent with such a position, though lack of space prevents entering the details here. However, the present article has gone further, arguing that the basic process also implies retrocausation and the possibility of additional causal variables, which were described in Sect. 5—effectively eliminating the need for a *dynamical* wave function collapse (at least in the case study considered).

longer need occupy us. HUP itself and the probabilistic results of QM are simply a consequence of the enormous complexity of the quantum potential, which acts to randomize the electron's motion. Or so Bohm argued [34]. He characterized the quantum potential as an objectively real field, somewhat like a classical force field.

However, the seeming simplicity of the BT picture can mislead, and it suffers from oddities that aren't shared by the present proposal. In particular, even though BT's field is taken as objectively real, it has no visible source, nor is it affected directly by the condition of the particles, being in these respects quite unlike other real fields, suggesting that the field may be a mathematical fiction. Moreover, since the strength of this field doesn't fall off with distance (unlike ordinary fields), it means that BT is manifestly non-local and contextual, in a deeper way than standard QM. This express non-locality and contextuality is a little ironic. Historically, hidden variable theories are associated with trying to *recover* locality, not deepen it.[17]

In addition to express non-locality, BT contains other (related) oddities, not present in the dual-world theory. These include (i) BT's empty waves, or 'inactive wave packets' in the configuration space; (ii) its requirement for a decoherence-preferred basis (decoherence itself being controversial, not least because of its 'tails' problem); (iii) its preferred reference frame: even though all the *statistical* results of the theory will be covariant, a particle guided in a non-local way will not, in general, be Lorentz-invariant [11], p. 285; and (iv) (in the context of psychophysical supervenience) its inability to specify exactly what physical state the mental state of an observer supervenes on: is it on the branch of the wave function occupied by Bohmian particles, or is it the relative positions of Bohmian particles? [25] Each gain in some particular respect seems offset by a loss in some other respect. It has been argued that the quantum potential itself is superfluous; that the *wave function* determines the evolution of the particles via Bohm's equation. "Particles are guided by the wave function, not pushed around by forces" [31], p. 121. However, the exact positions of the Bohmian particles cannot be measured even in principle, and there is dispute as to whether mass and charge are attributes of Bohmian particles or of the wave function.

Indeed, by 1962 Bohm himself accepted that his notion of the quantum potential, as it stood at the time, was rather unsatisfactory and arbitrary, and that the precise values of his fluctuating ψ-field and of the particle coordinates might be fairly criticized as being "empty of real content" [10], pp. 80-81. Though that didn't invalidate the theory as a logical self-consistent structure, it did attack its plausibility, as Bohm noted. For that reason, he thought that the potential couldn't be accepted as a definitive theory. "Rather, we should regard it as at best a schematic representation of some more plausible physical idea to which we hope to advance later, as we develop the theory further".

In view of the above problematic features, attempts have been made to reinterpret the ontology of Bohm's theory in several ways. One such is to reinterpret the (universal) wave function in Bohm's theory as having a lawlike ('nomological') existence rather than a physical existence. Lack of space precludes a discussion of the details. However, it should be noted that such a view is not without its own problems (see [25]), these arising essentially, according to the present author, from the same root causes as the problematic features of Bohm's original theory itself. (For discussions of BT, see e.g. [3, 12, 25, 31, 34].)

How to sum up? Bohm's theory brings to mind a picture in which a brilliant designer has

[17] It will be recalled that the dual-world theory also has a 'field', the strength of which doesn't fall off with distance, described in Sect. 5.2. It is the 'hail' of potentially resonant advanced photons, converging along light cones upon every atom and every particle in the universe, responsible for the causal decay of excited atomic states. However, this field is arguably local and has a physical source, being generated by the particles themselves undergoing the basic process.

been commissioned to make a model of a causally deterministic world, a world wherein half of the causal determinants lie in the past of systems and half in their future. The model is to be causally deterministic but the causal determinants lying in systems' future are not to be brought into the model.

9. Additional implications of the present theory; a prediction

The present (dual-world) theory has additional implications. Here are two, of which the first is also a prediction, in a sense. It concerns the so-called cosmological constant problem.

(i) According to quantum field-theoretical estimates, the vacuum energy density arising from vacuum fluctuations should be up to 120 orders of magnitude larger (in units of Planck mass) than the observational limit [32], p. 390. Because gravity interacts with all forms of energy, the concomitant breakdown of Euclidean geometry ought to be readily observable. However, the *observed* spacetime curvature arising from vacuum fluctuations is effectively *zero*. Clearly, there's a major breakdown somewhere in our theories, known as the cosmological constant problem. Even though the present theory possesses the equivalent of the QFT vacuum fluctuations (the fluctuations being associated with the particles themselves), the theory predicts a *zero* curvature, just as is observed. That's because the present theory contains no quantum-theoretical fields, as such, that undergo vacuum fluctuations. As for the present theory's equivalents of vacuum fluctuations, generated by its double transition\basic process, they are also simultaneously occurring in the conjugate dual world, but in reverse time; equivalently, in forward time but with negative energy. Thus, any spacetime curvature arising from that source is always exactly offset by an equal and opposite curvature. This seems a simple consequence of the ontic time-symmetry of the model.

(ii) The proposed 'basic process' may shed light on QED's\QFT's arcane subtraction formalism to remove its attendant infinities—known as renormalization. See [48], pp. 205-207.

10. Conclusion

This article has attempted an explanation of why measurements have determinate outcomes. It has put forward a retrocausal additional variable model of a quantum system's transformation from potentiality, represented by the ψ function, into actuality. The model is very simple, though hard to describe simply. It specifies what the additional variables are and how they work. It is causally deterministic, time-reversal invariant and 'local' in the sense that there is no action at a distance. The Heisenberg potentiality represented by the ψ function falls out of the model in a natural way, as does the ability of quantum systems to self-interfere when unobserved. The model's key element is a postulated deeper-level physical process, which was recently published by the present author [48]. The process—a very rapid periodic double transition process ('basic process'), between states of positive and negative energy that all matter particles forever undergo under the cover of HUP—is an extension and generalization of an early idea of Dirac's.

The model encompasses both fermionic and bosonic systems. Owing to its retrocausality, it readily evades the various 'no-go' theorems, such as Bell's theorem, usually taken to show the impossibility of a local hidden variable model that agrees with the predictions of QM.

The retrocausality of the model is shown to be closely connected with the operator formalism of quantum mechanics, which ensures that standard QM always lacks exactly half of the total data, or causal determinants (additional or 'hidden' variables), that would be required for arbitrarily accurate predictions. The model takes the missing half of the causal determinants to be located in the future of systems, associated with future boundary conditions, just as the

other half of the causal determinants is associated with past boundary conditions. It shows in detail, using the 'spontaneous' decay of an excited atomic state as a detailed case study, how the past and future causal determinants together completely determine the system's state at any instant. It does away with the need for a dynamical reduction postulate.

The model's\theory's implications are examined. The most significant of these is that there is more to the physical state than is reflected in the ψ function: QM's eigenvalue-eigenstate rule has failed. The resulting ontological status of the ψ function is described. Another implication is to do with the cosmological constant problem. The theory predicts a zero spacetime curvature arising from the energy density of vacuum fluctuations. A third is that the proposal seems to shed light on QED's arcane subtraction formalism to remove its attendant infinities—known as renormalization. The details of this last implication are in the author's previous article.

It is emphasized that the proposed theory is put forward as a heuristic. It is of course not a conclusive or definitive account of those aspects of quantum theory it covers. It deals with big questions and of necessity sidesteps many important and contentious interpretative issues owing to limitations of length. There are also gaps in the explanations that are proffered. For example, the theory does not attempt to explain why half of a QM system's causal determinants should always lie in its future, associated with future boundary conditions, save that such a hypothesis seems to work, and seems required to preserve temporal symmetry. This is an area requiring further work, as is the related question of the origin of quantization. Yet another is the precise relation of the fine-structure constant to the proposed interaction\resonance mechanism. However, it does seem to the author that a merit of the presently proposed theory, beside its heuristic potential, is that its explanations are not *ad hoc* explanations of this or that, but rather, explanations in terms of essentially a single idea, namely the proposed double transition\basic process.

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