Review Article

Psi-Onticity, Contextuality and Realism in Everettian Quantum Mechanics

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This article alleges that a pervasive contemporary species of Everettian quantum mechanics (EQM) fails to qualify as a consistent realist interpretation. It notes the lack of consensus amongst proponents of EQM as to questions central to its claim to realism. It argues nonetheless that four commitments can be attributed to the greater part of these accounts: Realism, Ontic Constituency, Universal Onticity and Weak Noncontextuality. It provides definitions of these commitments and then submits three examples of experimental configurations in which they appear to yield a contradiction. It concludes that the most tenable means by which to resolve this contradiction involves repudiating this doctrine of Realism within these formulations of EQM.

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Introduction

Whilst many of the alleged virtues of the Everettian perspective on quantum mechanics ("EQM") are subject to contention, its claim to qualify as a realist interpretation is rarely disputed. Questions as to the locality or nonlocality of the theory and questions as to preferred decompositions have absorbed the bulk of the commentary, whilst any debate over the realist credentials of EQM not only takes for granted that they belong to this interpretation but deploys them as a criticism: an excessive number real entities is postulated by Everett, it is said, to the point of ontological bloat.[1] Everettians themselves blazon realism unabashed. Wallace characterises EQM as a "traditionally realist" theory and its contents as a "literal description of reality."[1] Saunders, in his exploration of the matter of branch-counting within the theory describes it as "demonstrably a form of realism, on taking the quantum state to represent something existent,"[2] whilst in his analysis of structure in EQM he goes as far as to christen it "the only realist interpretation of quantum mechanics still standing."[3] Greaves is equally adamant as to the "physically real” nature of all branches of the Everettian wavefunction.[4] Chen is also explicit in his view that Everett qualifies as realist in the following sense: “The wave function represents something objective and mind-independent.”[5] M. Huber, T. Bigaj and D. Deutsch stake similar claims,[6][7][8] whilst DeWitt and Graham even declare EQM’s brand of realism so extreme as to be borderline “naïve.”[9]

It is, therefore, something of a dogma of the modern philosophy of physics that Everettianism constitutes a realist account of quantum mechanics. This article opposes this dogma. Specifically, it argues that pervasive contemporary species of EQM, such as advocated by Wallace and Saunders (*inter permulta alia*), entail the following inconsistent tetrad of propositions:

> **Realism**: EQM is psi-ontic.
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> **Ontic Constituency**: The ontic constituents of EQM belong to the following set of disjoint alternatives: relative states, branching structure or density operators.
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> **Universal Onticity:** Both decoherent and non-decoherent quantum states contain the ontic constituents of EQM.
>
> **Weak Noncontextuality**: The distribution of elements in the ontic state space of a system is independent of space-like separated measurement configurations.

This article outlines these four propositions that the author attributes to several formulations of EQM and justifies this attribution based on citations from recognizable proponents as well as logical inferences from its other stated commitments. It considers the variety of definitions of realism in the literature and ultimately adopts the Harrigan-Spekkens definition, drawn from their ontological models framework. It considers the equally rich variety of candidates for the main ontological commitment of EQM – that is, the most fundamental entities it considers extant – including the relative states of Everett, Timpson and Brown and the branching structure of Wallace and Saunders. It then argues that EQM is committed to the reality of the quantum state even in the absence of the decoherence effects taken to explain observations, lest the theory succumb to non-realism of an even stronger form. It then introduces an intuitive principle of noncontextuality, significantly weaker than the Bell-Kochen-Specker notion, which it attributes to EQM on the grounds of basic plausibility and consistency with no-signalling.[10] It then proceeds to examine three *gedankenexperiments* in which this tetrad yields contradiction: (i) isolated non-decoherent eigenstates; (ii) incompossible measurements corresponding to non-commuting observables, such as spin along orthogonal axes; and (iii) experimental configurations in which dynamical constraints preclude certain wavefunction components from being realised. It further considers the possibility of restoring consistency to the Everettian framework by denying some of these commitments, arguing that such a strategy harbours unpalatable ramifications. The conclusion follows that a consistent articulation of EQM must repudiate psi-onticity and curtail in keeping its aspiration to qualify as a meaningfully realist interpretation.

A plurality of realisms

In spite of the forthrightness of the Everettian commitment to realism, its expressions come in the form of diverse doctrines which are subject to no clear accord. Not only do they claim to be realist in different senses of this term; they identify different elements of the quantum formalism as being the most fundamental – or the only – real entity. S. Carroll, for example, reifies the constituents of Hilbert spaces, claiming that, “The fundamental ontology of the world consists of a vector in Hilbert space evolving according to the Schrödinger equation.”[11] For Saunders as well as Hartle, the relevant objects are decoherent histories represented by sequences of operators or bundles of Feynman paths: these explain the existence of independent branches in a dynamically selected basis and therefore account for the “quasiclassical realms” taken to be the contents of observation.[3](Hartle, J. (2012)) For B. DeWitt, it is the state vector supplemented with “a set of dynamical operator variables satisfying definite dynamical equations,”[12] which counts as a description of a real state. Wallace, perhaps the most distinguished of its proponents, identifies both density operators and branching structure as ontologically central at different episodes within his works:[13]

> These worlds are not part of the fundamental ontology of quantum theory - instead, they are to be understood as structures, or patterns, emergent from the underlying theory, through the dynamical process of decoherence. That they are structures in this sense does not mean that they are in any way unreal.
>
> My proposal...is very straightforward: just take the density operator of each subsystem to represent the intrinsic properties which that subsystem instantiates, just as the field values assigned to each spacetime point in electromagnetism represented the (electromagnetic intrinsic properties which that point instantiated.[1]

Similarly, P. Faglia, in his detailed recent paper “Non-separability, locality and criteria of reality” at times endows the density operator with the status of a definitive object in the case of the “Oxford” variant of EQM which, “Takes the density operator of a given system to represent the (intrinsic) physical state of the system and the unitary evolution of the density operator to describe the dynamical change of this physical state."[14] All of these commentators therefore nominate subtly different objects as the core posits of the ontology of EQM. Whilst these conceptions are overlapping in some respects, it is not at all obvious that they are equivalent. Carroll's vector in Hilbert space is not straightforwardly identifiable with the sequences of projectors forming chains such as $[C_\alpha = P^{t_n}_{\alpha_n} P^{t_{n-1}}_{\alpha_{n-1}} \cdots P^{t_1}_{\alpha_1}]$ and fulfilling (approximately) certain orthogonality conditions which imply that the states of the system in question evolve independently and without interference.[15][17] The density operator of a system, defined as $\rho = \sum_j p_j \ |\phi_j\rangle \langle\phi_j|$, is a mode of representation of quantum systems which is more general than the classical pure state and appropriate for the description of statistical mixtures of states, or where only a subsystem within a larger entangled system is under analysis; whatever is meant by "branching structure," it is no more identical to the latter mathematical object than it would be true to say that density operators exist only in branching systems. Thus, whilst unified in their attribution of realism to EQM, its advocates diverge in the objects to which they are willing to assign ontological primacy.

The same divergence holds of the *meaning* of the doctrine of realism asseverated by these prolocutors, and at large within the discourse of quantum foundations. It is useful to itemise several of the different senses of this term which feature in the relevant discussions, and to offer a brief synopsis of their differences. Firstly, an originary account was provided in the canonical Einstein-Podolsky-Rosen paper, often referred to as the "criterion of reality" principle.[3] This posits a sufficient condition for the existence of an element of reality rooted in the *predictability* of a corresponding measurement outcome, which distinguishes this from other formulations of quantum realism:

> If, without in any way disturbing a system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of reality corresponding to that quantity.[16]

Secondly, a precise and modern interpretation of this term was provided by Harrigan and Spekkens as part of the ontological models framework developed in their widely cited paper "Einstein, incompleteness, and the epistemic view of quantum states."[17] In this paper, "realism" is in effect coterminous with "psi-onticity," insofar as the latter provides a mathematical proxy for the former. The definition of this term is provided by the authors as follows:

> An ontological model is ψ-ontic if for any pair of preparation procedures, P_φ and P_ψ, associated with distinct quantum states φ and ψ, we have $p(\lambda|P_\varphi)p(\lambda|P_\psi) = 0$ for all λ.

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[17]

The intuition which equates this definition with realism is best discerned through the prism of the distinction between two ways of conceiving a quantum representation: according to one, the quantum state represents the world, that is, a distribution of ontic facts; according to the other, the quantum state does not represent such a distribution, but rather the epistemic state of an observer, viz. one's beliefs about the state of the world. The latter choice allows interpreters of quantum theory to circumvent the difficulties in interpreting the superposed, entangled or otherwise intractable quantum state: if it represents nothing real but rather the observer's uncertainty about the system's state the difficulties in interpreting quantum features such as superposition, discontinuity and collapse arguably abate. Such an interpretation of the quantum state was thought to be consilient with the hidden-variable theories propagated prior to Bell's pioneering work on nonlocality in the 1960s.[18] This intuition translates into the mathematical terms of the definition in the following way: a necessary condition for the quantum state to represent the world is that the distribution of ontic facts represented corresponds to no more than one such quantum state. Were more than one distribution of ontic facts to correspond to a quantum state, it would correspond to incompossible realities and fail to represent the world. Therefore, the quantum states must be non-overlapping over the quantum state space. Conversely, in the event that these states overlap, a natural interpretation is that they represent the observer's uncertainty as to the state the system occupies: the possibility of a distribution of ontic facts consistent with more than one quantum representation is by no means objectionable should the latter representation represent nothing observer-independent. It is in this sense that an equivalence may be drawn between psi-ontic and realist theories within this framework. Indeed, the authors take this nature of this distinction to be the one of the core motivating questions of their paper, posing it as follows at the outset of their study: "Does the quantum state represent reality or our knowledge of reality?"[17]

Thirdly and more recently, Waegell and McQueen developed several precise formalisations of locality and realism. Whilst reminiscent of the EPR criterion of reality, there are important points of difference visible in, for instance, the below "localized element of reality" claim:

> If an intervention and response happen in a finite region of space-time, and the response can be predicted with certainty, then there is an element of reality located only in that region that determines that response.[19]

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Here, the emphasis changes vis-à-vis the EPR reality criterion in two chief respects. For one, it is the relation of the element of reality to the experimental result – specifically, the determination of the latter by the former – as opposed to the correspondence between the element and the predictable quantity – which is in question. Further, this element must be located within the space-time region occupied by the response it determines and the intervention which precipitates it, hence the descriptor "localized." Waegell and McQueen in effect posit a function $R = f(e_R, I)$ which holds between the element e_R, intervention I and the response R whereby the latter is determined by the former two variables. The intervention could be the action of an observer, perhaps in configuring an apparatus as one might the axis of measurement of a Stern-Gerlach magnet.

This diversity of conceptions of realism in the general literature is paralleled by the diversity of such conceptions within the Everettian research paradigm. Wallace, for his part, at times echoes the Harrigan-Spekkens framework by claiming that sense in which EQM qualifies as realist is its literal reading of the quantum state by virtue of which, "To every different quantum state corresponds a different concrete way the world is."[1]. There is therefore no ontic state ("way the world is") corresponding to distinct quantum states. As do Harrigan and Spekkens, Wallace takes this as a sufficient condition for the completeness of EQM. At other times, he mirrors the Einsteinian conception, rooting the reality of the quantum state in the "predictability" and "explanatory power" of the patterns which constitute its observable manifestations.[4] Similarly, in a 1996 review article, Deutch sets out an implicit criterion for the reality of an object belonging to a physical theory: should that object best explain the outcomes of experiment, it corresponds to reality. Deutsch formulates a transcendental argument of sorts, framing belief in the existence of the posits of a given theory as conditions of the possibility of conducting science insofar as these posits correspond to observed regularities.[20] There is an innate plausibility to Deutsch's position: it is far from obvious how it could be in the least degree coherent or meaningful to make use of a theory for prediction and explanation, but deny it ontological content; to the experimenter probing the entities of the theory, they are no less real than everyday objects, albeit less readily observable in the absence of sophisticated apparatus. Saunders, in his "Branch Counting in the Everett Interpretation of Quantum Mechanics," takes a similar line, suggesting that the realism of EQM consists in its "taking the quantum state to represent something existent,"[2] (although the sense in which theories which contrast with EQM in this respect might represent non-existent phenomena is left unelaborated).

Despite these forming a far from exhaustive list of the conceptions of realism which have figured in the literature, the diversity among them serves well to illustrate the difficulties involved in warranting the

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sense in which, if at all, EQM qualifies as realist. It may be realist in one sense and non-realist in another. As argued in this section, these difficulties are twofold, entailing first of all the challenge of identifying exactly what it is within the theory that is real, and second of all the sense in which it is real. Nonetheless, for the purposes of this analysis, the following definition of realism, consonant with the Harrigan-Spekkens framework and also the writings of Wallace, will be adopted provisionally:

> **Realism**: EQM is psi-ontic.

Further – and less controversially – the following premise will be attributed to EQM, consistent with the fact noted above that a range of objects or structures feature as its fundamental posits.

> **Ontic Constituency**: The ontic constituents of EQM belong to the following set of disjoint alternatives: relative states, branching structure or density operators.[5]

The species of EQM analysed in this section is therefore committed to these two propositions.

An additional germane question as to the nature of EQM's commitment to realism arises in the context of decoherence theory, a domain of research which has become an indispensable facet of the contemporary Everettian worldview. Wallace, in particular, has produced extensive studies of the relation between decoherence and Everettianism since the turn of the Century. Decoherence involves the spontaneous interaction of a given system with its environment (such as a measurement apparatus or human observer) such that quantum-characteristic interference effects are suppressed and the density operator of the system is diagonalized, leading to the dynamical independence of different wave-function branches and approximately classical behaviour. It is therefore taken to be an essential ingredient in reconciling the seemingly unparsimonious assertion of the reality of incompossible wavefunction components with the quotidian experience of determinately localised macroscopic objects exhibiting well-defined values of energy and momentum. Within EQM, a problem naturally arises as to the status of the quantum state prior to decoherence. Is this state real in the same sense as is the post-decoherence state of the system? That is, is it true or false to assent to the following claim?

> **Universal Onticity:** Both decoherent and non-decoherent quantum states contain the ontic constituents of EQM.[6]

To this problem conflicting responses appear to have emerged from the research community. Wallace, for instance, seems to deny Universal Onticity, restricting the scope of claims about the reality of EQM's entities to instances of decoherence: branching structure is what is real, and branching structure only

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emerges in decohering systems.[1] Elsewhere, particularly when emphasising the density operator as the bearer of the designation “ontic” (as opposed to being an unphysical mathematical device),[1] the requirement for decoherence is seemingly absent. A similar ambiguity surfaces in his discussion of decoherent histories: it is unclear whether the *entire* histories of interacting subsystems are ascribed branching structure – and, by that token, a real state – throughout their lives if the property is fulfilled for *some* (later) history, or only for the duration of decoherence:

> The branching criterion then guarantees that if two realized histories coincide at some time (that is, assign the same projector to that time) then they coincide at all earlier times, and we will say that any set of histories with this property has a *branching structure*.[7]
>
> The branching-decoherence theorem…tells us that the vanishing of the decoherence function between any two distinct histories is a necessary and sufficient condition for a history space to have a branching structure.[1]

It is not at all obvious that the terms “branching structure” and “branching” are coterminous, opening up a natural justification for regarding branching structure as something which pre-exists decoherence and belongs to decohering states throughout their history.

For other commentators than Wallace, some of whom emphasise not so much branching structure but the global quantum state as the central ontic commitment of EQM, the status of Universal Onticity is also unclear. If the “fundamental ontology of the world” is a “vector in Hilbert space”[11] without the imposition of any further conditions which must be satisfied for this vector to be ontic, the quantum state is real both antecedent and subsequent to incidents of decoherence. Thus, for Carroll, the relevance of decoherence and quasi-classicality lies in its ability to recover everyday experiences and observed outcomes from the multiplicity of the quantum state, and not so much in grounding a distinction between real and unreal aspects of the formalism, as in the case of Wallace. Carroll thus draws a contrast between fundamental and emergent levels of the quantum picture and for an understanding of realism which is univocal over the two.

Everett’s own views are no more unequivocal. *Prima facie,* he proffers a deflationary analysis of the pre-decoherence state, declaring it meaningless to reify anything other than states of subsystems relative to that of the environment (observer, apparatus or whatever else).[21] If only relative states are meaningful then, presumably, only relative states are candidates for onticity; if relative states are defined only after decoherence occurs, and not prior to the interaction of the subsystems to which these states belong, there

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is no ontic state pre-decoherence. In the simple case of two spin-half particles being measured along parallel axes in a vacuum, the pre-measurement (and concomitantly pre-decoherence) state can be written:

$$\frac{1}{\sqrt{2}}|\uparrow\rangle_{A_1}\left(|\uparrow\rangle_{S_1}|\downarrow\rangle_{S_2}-|\downarrow\rangle_{S_1}|\uparrow\rangle_{S_2}\right)|\uparrow\rangle_{A_2} \tag{1}$$

Here, $|\uparrow\rangle_{A_1}$ and $|\uparrow\rangle_{A_2}$ refer to the pre-measurement states of the apparatus measuring particles 1 and 2, that is, before any readings have been taken; $|\uparrow\rangle_{S_1}|\downarrow\rangle_{S_2}$ and $|\downarrow\rangle_{S_1}|\uparrow\rangle_{S_2}$ refer to spin-up and spin-down states of the two subsystems. Here, neither S_1 nor S_2 have decohered and both are far in space-time from the event at which A_1 and A_2 are applied. The decisive question concerns whether these particles occupy definite *relative* states of spin – states relative to the distant apparatus. Everett's assertion of a fundamental relativity of states implies that, should they not, they fail to qualify as ontic. It is clear that the post-measurement state in which A_1 and A_2 adopt the values $\uparrow, \downarrow$ to reflect the state of subsystems S_1 and S_2 involves definite relative states:

$$\frac{1}{\sqrt{2}}\left(|\uparrow\rangle_{A_1}|\uparrow\rangle_{O_1}|\downarrow\rangle_{A_2}|\downarrow\rangle_{O_2}-|\downarrow\rangle_{A_1}|\downarrow\rangle_{O_1}|\uparrow\rangle_{A_2}|\uparrow\rangle_{O_2}\right) \tag{2}$$

This state, unlike the previous, is the result of obvious decoherence. The fact that relative states are defined in the same does not therefore impinge on the truth-value of Universal Onticity, requiring relative states, should they be anointed the central ontic commitment of EQM, to adopt relative states prior to decoherence. Nonetheless, this illustration is not irrefragable evidence that Everett licensed the denial of Universal Onticity within his interpretation. Whilst clearly committed to the foundational role of relative states, he also characterised the "universal wave function" as "the fundamental entity," and derogated the ontic import or "preferred role" of state transitions induced by measurements.[21] On this contrasting view, the distribution of the ontic characteristics of the global state are unaffected by local occurrences of decoherence. These remarks bear analogies to the proponents of maximalist realism with respect to the universal quantum state.

There are, therefore, contrasting perspectives which can be entertained within EQM as to the truth-value of Universal Onticity, with a discernible tendency for Everettians invested in branching structure to deny the reality of the pre-decoherence ontic state and for realists about the universal or global state to implicitly endorse it, according a diminished importance to local measurements.[8]

> $\mathbf{UO_1}$: Local density operators are the ontic constituents of EQM; local density operators pre-exist decoherence; Universal Onticity holds.

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$\mathbf{UO_2}$: Branching structure is the ontic constituent of EQM; branching structure belongs to the entirety of the histories of all decoherent states; the set of projectors comprising these histories include pre-decoherent states; Universal Onticity holds.

$\mathbf{UO_3}$: Branching structure is the ontic constituent of EQM; branching structure belongs only to decoherent states and not to their non-decoherent histories; Universal Onticity fails.

$\mathbf{UO_4}$: The global wave-function is the ontic constituent of EQM; the global wave-function exists whether or not any given local state is decoherent; Universal Onticity holds.

Propositions $\mathbf{UO_1}$ to $\mathbf{UO_4}$ capture only a modest few of the conceivable grounds for the assertion or denial of Universal Onticity within EQM. As a consequence, it makes sense to consider the ramifications both of an affirmation of and of a negation of Universal Onticity in order to reflect the different lines of Everettian thought appropriately. It is to this *analysandum* that the next section turns itself.

Universal Onticity and Weak Noncontextuality

Consider, first, the latter alternative: a denial of Universal Onticity. This would at first seem to be the natural position of the likes of Wallace, insofar as his pattern ontology seems agnostic with respect to the reality of the pre-decoherent state. Is this consistent with realism, as defined, given Ontic Constituency? The negation of this assertion is trivial to infer: if Universal Onticity is denied by virtue of the lack of any ontic state prior to decoherence, the ontic state is in effect a null set. However, there exists any number of quantum states corresponding to such a state: an isolated pure quantum state and its time-evolved counterpart correspond to this null set, both being pre-decoherent states without a related ontic state. This pair of states $|\ \varphi\rangle\,, |\ \phi\rangle =\ H|\ \varphi\rangle$ (with H denoting the Hamiltonian of the Schrödinger picture) can be associated with preparations $P_\varphi,\ P_\phi$ such that $p\left(\lambda|P_\varphi\right)p\left(\lambda|P_\phi\right) \neq 0$. Judged against the definition of realism provided above, one finds several quantum states corresponding to this ontic state, constituting a violation of psi-onticity by the standards of Harrigan and Spekkens. Thus, the insistence that only decoherent states are real does not therefore save the appearances of determinacy from the multiplicity of quantum superposition but redefine appearances as reality at the expense of the reality of what does not appear. Indeed, it could be said that EQM qualifies as a resonantly instrumentalist interpretation in the sense articulated by Timpson, insofar as it does not “seek to describe the laws governing unobservable things.”[22] Therefore, the alternative must be examined: Universal Onticity is affirmed such that both pre- and post-decoherence quantum states contain the ontic constituents of EQM.

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In order to see why this leads this variant of EQM into inconsistency, an additional proposition must be introduced:

> **Weak Noncontextuality**: The distribution of elements in the ontic state space of a system is independent of space-like separated measurement configurations.

The original conception of contextuality took on a prominent position in discussions of the foundations of physics after the work Bell, Kochen and Specker in the 1960s which, in simplified terms, revealed an inconsistency between (i) the assumption of the independence of physical parameters from measurement context and (ii) the canonical quantum formalism.[23] This ontological commitment is a weaker form of noncontextuality by comparison and closer in spirit to the principles of no action-at-a-distance which Everettians typically defend whilst conceding the violation of stronger principles such as probabilistic Bell nonlocality.[24][25] In particular, the independence of physical values from space-like separated measurements, as opposed to any measurements (including local measurements), is in question in this case. It is accordingly less controversial than the traditional Kochen-Specker presentation, and plausibly attributable to EQM.[10] Indeed, it is important to observe that, whilst Saunders, Wallace et. al. do endorse a form of contextuality with respect to branching structure, it is both distinct from and consistent with the affirmation of Weak Noncontextuality as an ontological principle. Further, Weak Noncontextuality is also distinct from and less controversial than the related notion of separability defined lucidly by Faglia in his 2024 paper. Without this distinction, there is indeed a risk that the current argument succumbs to a misrepresentation of EQM by attributing to it a commitment to separability which at least some Everettians are wont to eschew. Faglia defines separability as a constraint on related (sub) systems such that the intrinsic properties of the system supervene on the intrinsic properties of the subsystems. Non-separability, a feature of "Oxford" EQM, therefore implies the possibility of systems whose relations do not supervene on intrinsic properties of the related subsystems.[14] Whilst counter-intuitive, this possibility is an implicit feature of this school of Everettianism. Nonetheless, it is a stronger and more contentful principle than Weak Noncontextuality meaning, accordingly, the latter does not contradict non-separability, accommodating a relational definition of subsystem states. Were it otherwise, the ascription of Weak Noncontextuality to EQM would fail, leading to an immediate contradiction with non-separability.

This claim can be seen as a natural feature of the Everettian framework given (i) its (ostensible) commitment to Realism and (ii) the veracity of the no-signalling theorem. This theorem holds that

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measurement outcomes are independent of measurement settings configured at space-like separation. Thus, the probability of obtaining a measurement outcome A is independent of the setting x configured at space-like separation and depends only on the local setting λ. Given that one would, from the perspective of Realism, expect measurement outcomes to be functions of the ontic distribution lest the latter be explanatorily redundant, one is left with little choice but to embrace Weak Noncontextuality. Were this position denied, the ontic distribution would depend in some way on space-like separated measurement settings, but measurement outcomes would remain independent of the latter. This contradicts the transitive relationship between the variables in question, granted the premise that measurement outcomes are functions of ontic distributions. This reasoning is analogous to the argument that, if one variable is a function of another but independent of a third, the third must be independent of the second. Consequently, Weak Noncontextuality can be seen not so much as a supplementary and dubious premise but rather as a result of Realism given reasonable assumptions about the explanatory significance of the ontic state.

It is now possible to test the consistency of Realism, Ontic Constituency, Universal Onticity and Weak Noncontextuality, as defined above, by means of three examples. Consider first the case of a particle in a simple eigenstate $|\ \varphi\rangle$ in free space (and not, therefore, undergoing decoherence at the outset), long before any measurement is made, evolving as $|\ A_0\rangle|\ \varphi\rangle \rightarrow |\ A_1\rangle|\ \varphi$ where $|\ A_0\rangle$ and $|\ A_1\rangle$ are the initial and final states of the apparatus. Given Ontic Constituency, one of the following comprises the relevant ontic state: branching structure, density operators or relative states. Let the branching structure attributable to the subsystem be labelled $BrSt(|\ A_0\rangle, |\ \varphi\rangle)$, being patently a function of both the apparatus and the particle, and let the relative state of the apparatus-particle subsystems be $|\ A_0\rangle\ |\ \varphi\rangle$. Given Universal Onticity, the system occupies the ontic state represented by $BrSt(|\ A_0\rangle, |\ \varphi\rangle)$ or $|\ A_0\rangle\ |\ \varphi\rangle$ even in the absence of decoherence. Given Realism, to this ontic state corresponds only one quantum state; the distribution of quantum states is non-overlapping over the ontic state space. In the case of branching structure and relative states, Wallace is clear that this must be defined relative to a basis whose dynamical relevance manifests itself in decoherence.[1] However, this particle is far from any apparatus and space-like separated from its configuration. Whatever branching structure, relative state or density operator is attributed to it is therefore dependent on the space-like separated configuration, as is evident from the fact that $BrSt(|\ A_0\rangle, |\ \varphi\rangle)$, $|\ A_0\rangle\ |\ \varphi\rangle$ and $|\ A_0\rangle\langle A_0\ |\otimes|\ \varphi\rangle\langle\varphi\ |$ are functions of $|\ A_0\rangle$.[9] However, this involves a violation of Weak Noncontextuality: the basis dynamically selected by the measurement configuration which is ultimately responsible for the decoherence of the state impinges as a consequence upon its ontic state. The dynamical selection principle which picks out the set of branches or relative states which result from measurement leads to contradiction with this principle. This exposes the conjunction of Universal Onticity with Realism, Weak Noncontextuality and Ontic Constituency as contradictory.

Analogous reasoning can be applied to a number of other straightforward thought-experiments with similarly adverse implications for the form of EQM which endorses the four propositions itemised. By way of a second example, consider a more detailed scenario in which a spin-$\frac{1}{2}$ particle approaches a Stern-Gerlach magnet from a distance. The apparatus is configured to measure one of two orthogonal axes of measurement X, Y which are ascribed non-commuting operators. Therefore, no defined value for spin along one axis can be defined if the other is measured. The question which highlights the difficulties this presents for the status of Universal Onticity within EQM is as follows: Of the two possible spin values $\pm\frac{1}{2}$ along each axis, does the branching structure or relative state corresponding to one or to both of these exist before arrival at the magnet? By Universal Onticity and Ontic Constituency there must be *some* such ontic state; either the states $|\uparrow\rangle_X$, $|\downarrow\rangle_X$ (corresponding to positive and negative spin along axis X) or the states $|\uparrow\rangle_Y$, $|\downarrow\rangle_Y$ (corresponding to positive and negative spin along axis Y) or both of the two must qualify. The quantum states corresponding to these are $\frac{1}{\sqrt{2}}(|\uparrow\rangle_X + |\downarrow\rangle_X)$ and $\frac{1}{\sqrt{2}}(|\uparrow\rangle_Y + |\downarrow\rangle_Y)$. Of these two options, it is clear that the ontic state cannot be identified with both of these two states; of the two, branching can occur in one basis only. Were both taken to be ontic, branching structure and relative states would exist both in bases which branch and those which never branch, making the concept redundant as a mark of anything real and posing a flagrant inconsistency with any authoritative Everettian account of decoherence. However, if only the basis picked out by the dynamics of decoherence once the particle reaches the apparatus is considered ontic, a problem ensues: the orientation and reorientation of the magnet at a distance untraversable by any non-superluminal signal violates Weak Noncontextuality. No information about the ultimate measurement setting of the apparatus is given which could select one of the two bases as embedding branching structure. Thus, the case of incompossible measurements such as orthogonal axes of spin mires in inconsistency the four propositions ascribed to EQM in previous paragraphs. Indeed, one could contrive a more dramatic illustration by imagining a variation in which the Stern-Gerlach device alternates at high frequency between the two possible axes of measurement, perhaps based on a quasi-random variable such as various properties of incident radiation arriving at the device from a great distance.

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Finally, this inconsistency can be cast into further relief by considering examples of dynamically incompossible measurements – measurements, that is, in which contingent features of the interaction between subsystem and apparatus rules out the possibility of definite states of certain observables or definite outcomes relative to certain bases. This stands in contrast to attempts to measure commuting observables, since in these latter cases each measurement *in principle* excludes well-defined states of the other, independent of the measurement configuration. The persistence of this contradiction between the tetrad of propositions attributed to EQM throughout this argument in this case goes to show that the clash between Weak Noncontextuality and the other propositions which express Everettian realism is not merely an implication of the uncertainty principle. Otherwise, it may have been objected that the impossibility of associating with the quantum state an ontic distribution which is independent of the measurement configuration is a general consequence of the quantum formalism rather than a specific consequence of realist EQM.

In this regard, the quantum eraser variation of the Wheeler delayed choice experiment provides an illustrative case (although a number of others could be chosen).[26] Here, photon beams emitted from a source approach an absorptive screen with two slits. Adjacent to these two slits are devices ("type-II phase matching nonlinear optical crystals"[26]) which have the effect of duplicating each photon pair (with the frequency of each reduced in accordance with conservation principles). Subsequently, a prism is used to project the resultant beams along divergent paths, producing two pairs of beams, each containing a beam emitted from one slit as well as a beam emitted from the other. The first pair, P_S, is directed towards a screen (similar to the well-known device which displays interference fringes in the double-slit experiment). The second pair, P_I, is subjected to a more complicated arrangement at some distance from the original slits: the two beams are incident on distinct half-silvered mirrors (each with a 50% probability of reflecting an incident particle and a 50% probability of transmitting it). These mirrors are arranged in conjunction with a series of detectors such that the following four outcomes are possible:

- **Detector one registers a photon:** The photon must have emerged from the first slit and was reflected by the mirror.
- **Detector two registers a photon:** The photon must have emerged from the second slit and was reflected by the mirror.
- **Detector three registers a photon:** The photon could have come from either slit and was transmitted by the mirror.

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- **Detector four registers a photon:** The photon could have come from either slit and was transmitted by the mirror.

The uncertainty over the origin of photons registered at the latter two detectors is achieved by positioning an additional mirror so that any photons in P_I which are transmitted by the first mirrors could arrive at detectors three or four depending on whether they are reflected or transmission by this mirror.[10] If this mirror were removed, the third and fourth detectors would each register if and only if the photon originated from one of the two slits. Despite that this sequence of mirrors is arbitrarily further away from the slits than the screen, the surprising result of the experiment is that detections at stations one and two correlate with the destruction of the interference pattern produced by P_S, and that detections at stations three and four correlate with the formation of the interference pattern produced by P_S. This amounts to a novel conceptualization of seemingly nonlocal effects insofar as the presence or absence of the final mirror in the arrangement surrounding P_I impacts the formation of a pattern which one would, from a classical perspective, expect to have been determined in the distant past, considering the far greater distance between the mirror arrangement and the slits when compared with the distance to the screen. A choice made arbitrarily far into the relative future by the experimenter would have implications for the pattern formed on a screen adjacent to the detector.

How does this further elucidate the inconsistency of the tetrad of propositions cited, being Realism, Universal Onticity, Ontic Constituency and Weak Noncontextuality? The inconsistency arises from precisely the counter-intuitive feature of the experiment identified above – the influence of the second mirror which can be inserted and withdrawn at the whim of the experimenter (or as the outcome of any extraneous random process with binary results). By Weak Noncontextuality, the measurement configuration represented by the insertion or withdrawal of this mirror cannot affect the ontic distribution of the distant setup; these are space-like separated, assuming the distance is sufficiently great. Again, the ontic constituents of the state are comprised by relative states, branching structure and density operators. The relative state of P_S

The initial state of the beam pairs can be represented as follows:

$$|\ \varphi\rangle_{DCQE} = \frac{1}{\sqrt{2}}(|\ U\rangle_S \otimes |\ u\rangle_I + |\ L\rangle_S \otimes|\ l\rangle_I) \tag{3}$$

Here $|\ U\rangle_S$ represents the state of the P_S-beam-through the upper slit and $|\ L\rangle_S$ the state of the P_S-beam through the lower slit; $|\ u\rangle_I$ represents the state of the P_I-beam-through the upper slit and

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$| l\rangle_I$ the state of the P_S-beam through the lower slit. As the upper photon progresses to the screen, the state becomes:

$$| \varphi\rangle_{DCQE} = \frac{1}{\sqrt{2}}(\int dx\psi_U(x)| x\rangle_S \otimes | u\rangle_I + \psi_L(x)| x\rangle_S \otimes | l\rangle_I) \tag{4}$$

Now, two quantum states can be distinguished, depending on the presence or absence of the second mirror in the region of the P_I-beam: it is this device which "erases" information as to whether this beam passed through the upper or lower slit from the records of the third and fourth detectors if present whilst, in its absence, this information is available. These states can be represented in the following way. First, label the four possible detector modes $| 1\rangle_I$, $| 2\rangle_I$, $| 3\rangle_I$, $| 4\rangle_I$. Secondly, represent the evolution of $| u\rangle_I$ and $| l\rangle_I$thus:

$$| u\rangle_I \to \frac{1}{2}(| 1\rangle_I + e^{i\theta_1}| 2\rangle_I + \sqrt{2}e^{i\alpha}| 4\rangle_I) \tag{5}$$

$$| l\rangle_I \to \frac{1}{2}(e^{i\theta_2}| 1\rangle_I - | 2\rangle_I + \sqrt{2}e^{i\beta}| 3\rangle_I) \tag{6}$$

Therefore, the evolution of the combined state $| \varphi\rangle_{DCQE}$ in the presence of the final mirror is given by:

$$\begin{aligned} | \varphi\rangle_{DCQE} \to \frac{1}{2\sqrt{2}}[(| U\rangle_S + e^{i\theta_2}| L\rangle_S) \otimes | 1\rangle_I + (e^{i\theta_1}| U\rangle_S - | L\rangle_S) \otimes | 2\rangle_I \\ + \sqrt{2}e^{i\beta} | L\rangle_S \otimes | 3\rangle_I + \sqrt{2}e^{i\alpha} | U\rangle_S \otimes | 4\rangle_I] \end{aligned} \tag{7}$$

With the mirror removed, however, the state transition becomes:

$$| \varphi\rangle_{DCQE} \to \frac{1}{2}[| U\rangle_S \otimes (| 1\rangle_I + | 4\rangle_I) + | L\rangle_S \otimes (| 2\rangle_I + | 3\rangle_I)] \tag{8}$$

It is evident that, in the latter case, any of the detector states $| 1\rangle_I$, $| 2\rangle_I$, $| 3\rangle_I$, $| 4\rangle_I$ is associated uniquely with one of the states of the P_S-beam $| U\rangle_S, | L\rangle_S$, representing the provision of which-way information about the P_S-beam. However, this provision does not obtain in the former case, with only $| 3\rangle_I$ and $| 4\rangle_I$ associated with a unique member of $| U\rangle_S, | L\rangle_S$ and $| 1\rangle_I, | 2\rangle_I$ associated with both. Given the differences between these two expressions, one must ask: is it possible to maintain that the ontic constituents of the state obey Weak Noncontextuality as well as Realism and Universal Onticity? This would imply that the removal of the mirror has no effect on the relative states of the combined system, nor the branching structure which gives rise to these relative states. However, this cannot be the case. Universal Onticity implies that, prior to any detector firing or any photons arriving at the screen which receives the P_S-beam, the ontic constituents of the state asserted by EQM exist. However, the relative states or branching structures entailed by the two different representations of $| \varphi\rangle_{DCQE}$ are patently distinct, with the state representation corresponding to the present mirror encoding possibilities debarred in its absence. Given a sufficiently vast device, the insertion or removal of the mirror will be space-like separated from the reception of the P_S-beam at the screen. Therefore, Weak Noncontextuality is violated: a space-like separated measurement configuration, being the final mirror inserted or removed, alters the distribution of the elements which comprise the ontic space. Thus, the conjunction of Weak Noncontextuality, Realism, Universal Onticity and Ontic Constituency is contradictory.

This conclusion is corroborated by an examination of the density matrix formalism. This is relevant insofar as density matrices have been nominated, albeit murkily, by EQM as among the ontic constituents of the quantum state, whereas the analysis of the previous paragraph relates only to the other two main candidates – relative states and branching structure. First, consider the expression for the joint, global system with the final mirror-recombiner present in the vicinity of the P_I-beam:

$$\rho_{SI} = |\ \varphi\rangle_{DCQE}\langle\varphi\ |_{DCQE} = \sum_{X,Y}\sum_{p,q=1}^{4} c_{Xp}c_{Yq}{}^{*}(\ |X\rangle_s\langle Y\ |)\otimes(\ |p\rangle_I\langle q\ |) \tag{9}$$

Here, X, Y are variables belonging to the set $\{|\ U\rangle_S, |\ L\rangle_S\}$.

Second, consider the reduced density matrix corresponding to the subsystem explored by the P_S-beam, which follows from tracing over states of the P_I-beam:

$$\begin{aligned} \rho_S = Tr_i(\rho_{SI}) = \\ \sum_{p=1}^{4}\sum_{X,Y} c_{Xp}c_{Yq}{}^{*}(\ |X\rangle_s\langle Y\ |) = (\sum_{p=1}^{4}|c_{Up}|^2)\ |U\rangle_S\langle U\ |_S + (\sum_{p=1}^{4}|c_{Lp}|^2)\ |L\rangle_S\langle L\ |_S \\ + (\sum_{p=1}^{4} c_{Lp}c_{UP}{}^{*})\ |U\rangle_S\langle L\ |_S + (\sum_{p=1}^{4} c_{Up}c_{LP}{}^{*})\ |L\rangle_S\langle U\ |_S \end{aligned} \tag{10}$$

Given that off-diagonal terms vanish due to the orthogonality of the states of the P_I-beam detectors and also that $\sum_{p=1}^{4}|c_{Up}|^2 = \sum_{p=1}^{4}|c_{Lp}|^2 = \frac{1}{2}$, this reduces to:

$$\rho_S = \frac{1}{2}\ (|U\rangle_S\langle U\ |_S + \ |L\rangle_S\langle L\ |_S) \tag{11}$$

This expression is identical to the expression applicable in the case that the final mirror-recombiner is absent in the vicinity of the P_I-beam. Thirdly, consider the expression for the joint, global system in this latter case:

$$\rho'_S = |\ \varphi'\rangle_{DCQE}\langle\varphi'\ |_{DCQE} = \sum_{X,Y}\sum_{p,q=1}^{4} c_{Xp}c_{Yq}{}^{*}(\ |X\rangle_s\langle Y\ |)\otimes(\ |p\rangle_I\langle q\ |) \tag{12}$$

This expression differs from its counterpart in the presence of the final mirror-recombiner, unlike the reduced density matrix corresponding to the subsystem explored by the P_S-beam which, as stated, is identical whether or not this device is present. This difference arises from the fact that the cross terms which regulate the conditional probability of a particle arriving at position x on the detection screen for the P_S-beam given its reception at a given detector for the P_I-beam $c_{X_p}c_{Y_q}{}^*$are vanishing in the absence of the mirror. This signifies the suppression of the interference pattern insofar as there is no registration on a given detector p consistent with non-zero amplitudes for both of the elements in $\{|\ U\rangle_S, |\ L\rangle_S\}$, that is, passage through both of the P_S-beam slits and subsequent interference.

In this context, one may proceed to ask which of the above objects constitute the relevant ontic state in EQM. If the joint density matrix is considered ontic, then an obvious violation of Weak Noncontextuality follows: since the two matrices differ, the ontic state would be influenced by alterations made to space-like separated measurement configurations, *qua* the insertion or removal of the final mirror. The alternative is to take the reduced density matrix which results from tracing over states of the P_I-beam and is therefore independent of measurement configurations at the distant system. This interpretation enjoys the advantage that these matrices are, unlike in the joint case, identical regardless of the presence or absence of the mirror, a fact which *prima facie* enables its reconciliation with Weak Noncontextuality. However, this strategy only shifts the nexus of inconsistency rather than resolving it: it still entails a violation of Realism. This is due to the fact that there are an infinite number of distinct global pure states consistent with ρ_S in this instance. There is thus no injective relationship between these global states and the reduced density operator. Realism, by contrast, requires that the quantum state is psi-ontic insofar as only one quantum state, that is, the global pure state, corresponds to what this line of interpretation alleges to be the ontic state, that is, ρ_S. Regardless of which of the two candidates for the ontic state (either the reduced or the joint density operator) are chosen, the four propositions distinctive of EQM's character as a realist interpretation prove inconsistent with the quantum eraser configuration analysed in this section.

Conclusion

Whilst protean, the Everettian aspiration to qualify as a realist interpretation of quantum mechanics can be captured in four basic contentions stated or implied by many of its proponents. Firstly, the quantum state is real in the sense that it is psi-ontic. Secondly, the ontic constituents of EQM typically belong to the following set of disjoint alternatives: relative states, branching structure or density operators. Thirdly, both decoherent and non-decoherent quantum states contain the ontic constituents of EQM. Finally, the distribution of elements in the ontic state space of a system is independent of space-like separated measurement configurations. These contentions can be glossed as Realism, Ontic Constituency, Universal Onticity and Weak Noncontextuality. The first three of these contentions are discernible in the works of leading devotees of the theory including Wallace, Saunders, Timpson, Carroll, Dewitt and Deutsch. The final contention is a supplementary principle which can be viewed as a consequence of the conjunction of Realism with the quantum no-signalling theorem. As a weaker (less controversial) principle than more traditional, Bell-Kochen-Specker inspired definitions of contextuality – and one which is consistent with the forms of contextuality which *are* conceded by Everettians, such as the dependence of branching structure on measurement configurations – it is difficult for EQM to reject without unwelcome consequences.

The analysis of the previous sections seeks to show that these four commitments are inconsistent in the context of several familiar experimental configurations. It considers (i) a simple eigenstate in free space, (ii) in-principle incompossible measurements corresponding to non-commuting operators, and (iii) incompossible measurements which arise from contingent features of the apparatus configuration, as in the case of the delayed-choice quantum eraser. So, how might EQM resolve this inconsistency? This can be achieved only at the cost of denying one of the two of Realism and Ontic Constituency. If Universal Onticity be denied then Realism fails regardless; as argued above, it follows from this that EQM qualifies as an instrumentalist interpretation in the sense articulated by and cited from Timpson.[22] If Weak Noncontextuality be denied then one of Realism and no-signalling must presumably be abandoned in sympathy. Moreover, it would be incumbent on any defence which proceeds from these denials to explain how they resolve the contradictions generated from examples (i)-(iii). Since Ontic Constituency simply elaborates the objects EQM takes as candidates for ontic constituents of the state, rejecting this proposition leaves the theory devoid of any element which could qualify it as realist, resulting in a Realism with no specified object being real. Pervasive contemporary species of EQM are therefore confronted with an unenviable quandary: grant that the interpretation fails to cohere with principles fundamental to modern quantum mechanics or renounce their commitment to Realism.

Footnotes

[1] It is to these charges that more sophisticated modern formulations of the theory respond using the dynamics of decoherence.

[2] A complete, first-principles explanation of these conceptualizations of Everettian ontology is beyond the scope of this review.

[3] In Waegell, M. and McQueen, K.[19]., this principle is referred to as the λ-criterion.

[4] [13]. Wallace refers to this conception as “Dennett’s criterion.”

[5] It is conceded that this list is not exhaustive and acknowledged that the Hilbert-space realist approach of Carroll and others is omitted from this set of alternatives and lies left beyond the scope of the author’s argument.

[6] It should be noted that the definition of decoherence is admitted to be vague by EQM advocates; this does not undermine the line of argument of this article, which considers non-decoherent states to be those for which interference phenomena are dynamically relevant.

[7] [1]. It should be borne in mind that Wallace is consistently open about the approximateness of the branching process and eschews the temptation to propose a criterion delineating decoherent from non-decoherent states with sharpness.

[8] Many of these accounts rest on a distinction of sorts between the local and global properties of this state, where the former are relegated in one way or another to the status of subjective appearances and the latter taken as in some sense more fundamental, enabling advocates to explain away some of the counter-intuitive aspects of the local dynamics, such as the ostensible ability of entangled measurements performed at a subsystem to influence the status of space-like separated subsystems. A detailed analysis of the ground of this distinction is beyond the scope of this section.

[9] More will be said later about the reasons why the *reduced* density operator which traces over states of the distant device and may seem a plausible ontological alternative to the joint state does not assist in resolving this tension.

[10] A far richer presentation of this setting is available in Kim, Y. et al.[26] and is omitted from the present discussion in the interests of brevity.

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