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Review

Defending Many Worlds via Case Discrimination: An Attempt to Showcase the Conceptual Incoherence of Anti-Realist Interpretations and Relational Quantum Mechanics

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Abstract: In this work, an alternative attempt to motivate the Many-Worlds Interpretation (MWI) is undertaken. The usual way of arguing for MWI mostly revolves around how it might solve the measurement problem in a more straightforward and concise manner than rival interpretations. However, here an effort is made to defend MWI in an indirect manner, namely via repeated case discrimination and a process of 'conceptual elimination'. That is, it will be argued that its major rivals, with QBism and Relational Quantum-Mechanics being among the most noteworthy ones, either face conceptual incoherence *or* conceptually collapse into a variant of MWI. Finally, it is argued that hidden-variable theories face severe challenges when being applied to Quantum Field Theory such that appropriate modifications may lead back to MWI, thereby purportedly leaving MWI as the only viable option.

Keywords: foundations of physics; interpretations of quantum mechanics; QBism; relational quantum mechanics; Informational Monism; Ontic Structural Realism; many worlds; inference to the best explanation; case discrimination; counterfactuals

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1. Introduction

More than nine decades after its conception, what quantum mechanics is actually telling us, or, for that matter, what the actual ontological implications of the formalism are, is still hotly debated.

While its empirical adequacy has been experimentally confirmed countless times up until today, the theory being implemented into virtually all contemporary electronics and digital technology, its metaphysical implications and its fundamental ontology remain to be debated; this is without apparent progress or consensus in terms of which direction or approach can be regarded as the most promising. Despite, or rather, *because* of this standstill, critics of such quantum-mechanical interpretational disputes tend to object something along the following lines: 'what the formalism *means* is a nonsensical question since it eventually cumulates into nothing but endless debates over semantics without any visible progress, whereas technical progress—continuing its implementation into technical applications and working out the details—eventually will, albeit indirectly, resolve the riddle in near or distant future by revealing new structure'.

However, here I strongly oppose this view: not only do I believe that ontological commitments in fact *do* affect the fruitfulness of future empirical findings and potential breakthroughs, but also, that from a meta-physical viewpoint, we already are in a position to reasonably subject the various interpretations to a high-level conceptual analysis and thereby to identify the most truthful interpretation in an *epistemological coherentist* fashion: that is, while each piece of argumentation in and by itself may only have moderate persuasive force, the mutual enforcement of all linked pieces may lead to an exponential increase in credibility. In other words, I shall argue that in fact, all the relevant meta-theoretical pieces already have been gathered in order to heuristically arrive at a definite decision in terms of *one* veritable interpretation. However, so far, rarely one single work has collected, discussed and juxtaposed an amount of arguments which seems reasonable for such decision. My humble contribution shall hence be to provide, in this spirit, a brief, but hopefully adequate, big-picture overview; - this is one which however, as I shall argue, already speaks for itself in terms of favoring the one interpretation that regards the formalism to be empirically adequate *and* complete.

2. Methods

Let me begin with some preliminary remarks: firstly, in this review, I shall claim that the Many Worlds Interpretation (MWI), and the decoherence-based MWI (dbMWI) in particular, will be the only interpretation to leave this conceptual 'Mexican standoff' as an alive and winning party. However, I will do so indirectly, that is, by mainly analyzing the competitors and highlighting the problems *they* face and how the respective dissolutions might ultimately lead to a conceptual collapse into MWI. Thus, up until a final section in which the better part of this work culminates, I will not go deeper into the details of MWI itself. Secondly, although for the purpose of this paper and for reasons of simplicity it may be of higher priority that all variants of MWI stand united against rival interpretations, I still take dbMWI to be the most straightforward and concise version of MWI (as I will discuss in the final subsections). Hence, if not explicitly stated otherwise, from now on, MWI refers to dbMWI.

Numerous different interpretations of Quantum-Mechanics (QM), a number impossible to keep track of, seem to have matured into a noteworthy state, an affair which is an overkill that seemingly defies any attempt at conceptual disentanglement (Ref. [1] provides a table of 13 different quantum mechanical interpretations/theories and their respective features and properties. This can be taken as a good overview for introductory purposes, although, obviously, some new and recent developments are not even considered). However here, despite, or rather *because* of this confusion, I want to demonstrate the possibility of defending MWI in the spirit of *reductio ad absurdum*, that is, by showing that any rival interpretation or theory might lead to some or other form of conceptual incoherence or challenge, the dissolution of which leads back to MWI eventually. The latter process may also be understood as an attempt to arrive at MWI by an inference to the best explanation, one which also relies heavily on the use of counterfactuals.

However, some reasonable constrictions are still in order, constrictions which hopefully strike the right balance between scope, simplicity and adequacy. In Section 3.1, I will therefore choose a coarse-grained view and restrict myself to the discussion of *anti-realist* interpretations in general. While there are noteworthy fine-grained distinctions between several views belonging to this group, for the aim of this paper, it might nevertheless suffice to regard the default, the Copenhagen Interpretation (CI) that is, but also the QBism and informational 'neo-CI', - due to their recent growth in popularity, as relevant placeholders for *any* anti-realist interpretation. Their phenomenological emphasis of the act of observation, and instrumentalist/pragmatist tradition heritage are good enough demarcating criteria for being paradigmatic examples of *any* anti-realist interpretation (see [2–4] for some further general and introductory discussions of and around CI).

Next, Section 3.2 will be solely dedicated to a discussion of Relational Quantum Mechanics (RQM). This one is a noteworthy exception, for two reasons: firstly, although its founder Carlo Rovelli clearly emphasizes that it should be understood in realist terms, it nevertheless contains elements that likewise attract people with anti-realist leanings. Secondly, as I shall argue, it might actually be closer to MWI than it is generally perceived. The sheer fact that MWI is also regarded as the 'relative state interpretation' [5,6] may however already hint at this. Stronger still, I shall ultimately argue that RQM must collapse into a version of MWI *or* it is conceptually incoherent.

I will claim that, up to this point, anti-realist advocates still have two realist options left, hidden-variables theory or MWI. Hence, in Section 3.3, I shall review two of the most established 'realist rivals' of MWI, which are Bohmian mechanics (BM) [7] and Objective Collapse Theories (OCT) [8], such as the Ghirardi–Rimini–Weber model (GRW) [9]. I will come to the conclusion that in this domain, conceptual difficulties are particularly severe when considering application in quantum field theoretic (QFT) contexts.

Finally, after having purportedly laid bare the conceptually problematic baggage of any major alternative, I will inspect the core of QM which remained untouched throughout the analysis, more closely. I will then briefly review how 'pure' QM plus decoherence straightforwardly leads to MWI and how decoherence may ultimately also provide a solution to the preferred basis and probability problem. Before briefly addressing the sociological reasons for why the physics community seemingly still favors CI, I will come to the conclusion that we already have all the rationale necessary for putting MWI in the consensus.

3. Juxtaposing QM Interpretations via Repeated Case Discriminations

3.1. Anti-Realist Interpretations

3.1.1. The Copenhagen Interpretation

Let us begin with common and rather established arguments against the Copenhagen Interpretation (CI). Despite its challenges, the still most common way to justify (and thereby 'quasi-solving´ the measurement-problem) the apparent incompleteness of the formula is orthodox CI, as is notably found in textbooks. According to CI, the formalism is not incomplete in the nomological sense, but only such that it fails to factor in the causal efficacy of the observer or measurement apparatus. Whether considered as a conscious being or a mere device, it is, for the CI advocate at any rate, a macroscopic *non-QM* entity that is supposed to 'collapse' a probabilistic distribution into a reified physical and substantial, definite outcome. Setting aside its ' . . . *and then a miracle occurs* . . . ' obscurity, and ignoring other general issues regarding two-realm metaphysics or Metaphysical Dualism (MD) for the moment, the conceptual difficulties remain severe; as such, it necessarily follows that the entity responsible for the wavefunction collapse must be in some sense acting *beyond* the micro-physical realm in order to avoid contradiction; in other words, it must be 'non-quantum physical'. This however violates the thesis that macro-physical objects are composed of micro-physical ones (it would itself be in the very superposition it ought to collapse if *not*). It is needless to say that this alleged solution to the measurement problem is beyond a serious contemporary scientific attitude.

What is more, the Heisenberg Cut involved in CI seems rather arbitrary and may be in conflict with the overall goal of science, namely, the search for further levels of unification. Howe justified is the rationale that the laws of quantum mechanics break down at a certain limit? If nothing else, ever more sophisticated experiments have provided evidence to the contrary, i.e., they have demonstrated that there seems to be no absolute upper size limit for interference, which is in consonance with the unificatory mission of science [10]. That being said, while quantum and quasi-classical domains surely are *qualitatively* different, it is still the case that quantum-mechanical (QM) laws' convergence towards the classical limit is a *continuous*, rather than an *abrupt* affair.

Furthermore, one could bring forth a general objection against any interpretation that relies on a so-called '*conscious* observer'-dependence. For a start, even *if* a (either cartesian MD or physicalist) mind of an agent may be responsible for both the nature of the wavefunction and the measurement (updating or collapsing) process, one might still argue that this situation *in-itself* requires a mind-*independent* mechanism that mediates such observer–object correspondence in the first place; indeed, such a (inevitably hidden-variable-involving) mechanism, in turn, *must* then objectively be *in the world*, either as a physical, or perhaps 'meta-physical', structure; however, at any rate, and that is the crucial point I intend to make, it is as something *independent* of the mind. When, at this point, neither accepting full blown Metaphysical Monistic Idealism (MI) nor posing a mind–matter correspondence mechanism is an option, while mental causal efficacy is still assumed as it purportedly is by QBist interpreters of 'Wheeler´s *Participatory Universe*' [11–13], conceptual incoherence seems to arise. A structurally similar argument can also be brought forth against the claim that measurement *devices* are responsible for the collapse; indeed, an objective mind-independent mechanism would also be required for explaining such ‘top-down causation’, - eventually turning also *this* reading of CI into a hidden variable theory).

Finally, in order to ward off other common, albeit rather handwavy ‘solutions’ to the measurement problem, I shall quote Dürr and Lazarovici [14], who state the following:

> “*(simply) pointing to Born’s rule does not avoid the measurement problem*”.

This is so because it alone can explain neither the interference phenomena of the wave-function components, nor why a definite outcome appears at the phenomenological level. Hence, the explanatory options that essentially remain are *either* hidden nomological variables *or* to regard the formalism as physically substantial and *complete*; however, merely pointing to the instrumental or toolkit-like nature of the quantum formalism will not do. In the subsequent subsection, we will rephrase this state of affairs explicitly in terms of truthmakers.

3.1.2. QBism and the Problem of Truthmakers

It hence appears as if anti-realist interpretations in general only sweep the interpretational issue under the carpet, instead of actually solving it. Unless one accepts full blown MI, something which is rarely the case among defenders of *any* anti-realist or instrumentalist interpretation, the anti-realist still owes us an explanation regarding what it is that creates the empirical adequacy of such an instrumentalist wave function. In other words, they seemingly commit the categorical mistake of speaking of representational patterns without ever dissolving the riddle of what *it is that is being represented* or even downright deny the existence of the latter. David Wallace puts it well:

> “*(A)ny viable (…) account of quantum mechanics will owe us another account of what the probabilities encoded in the quantum state are probabilities of, of what the physical features of systems are. Or, put in more pragmatic terms: what the non-quantum features of a system are such that the quantum state is a tool for answering questions about those features*.” [2], (p. 12)

Clearly observable structures such as interference patterns in the double-slit experiments might in themselves already rule out an ontological status as *mere calculational device*. Tim Maudlin has a similar take on this when he writes the following:

> “*one might also wonder how any theory that is not ψ-ontic could possibly account for interference phenomena, such as the Double-Slit experiment*”. [15]

A fortiori, The unequivocal ‘balloon’-like structures that appear when observing hydrogen atoms (with non-vanishing angular momentum), albeit being only a *diachronic* ensemble of particle detections, make it equally plausible to conclude that there is at least *some real* physical structure that causes such distinguishable ‘real patterns’ [16]. Stronger still, they also causally affect each other, which can be taken as prototypical for ‘being physical’. Wallace, likewise, states the following:

> “*In physics jargon, there is interference between the ψ_x and ψ_y parts of the state, so that the x outcome is reinforced and the y outcome is cancelled out; interference phenomena like this are very general, and rule out the possibility of a probabilistic interpretation of the state space*.” [17], (p. 5, my emphasis)

In other words, epistemic interpretations alone cannot explain such patterns and interactions and it seems to be equally ill-founded to call them *instrumental constructs*, as much as it would be to call snowflakes *instrumental constructs.* What they have in common is that both phenomena exist in the world and both involve an ensemble of a detectable particle-like structure, whereas the former supposedly only exists as a *temporal* diachronic (as opposed to a synchronic) physical ensemble within spacetime; however, this is a difference that should not be crucial for the point being made. At any rate, there are good reasons to conclude that *physical* truthmakers are what is being represented by the QM formulism. Wallace elaborates this general argument by stating the following:

> "*In any concrete instantiation of quantum theory, the observables over which probability distributions are defined are particle positions, field strengths, collective spins and the like. The only way to say anything non-circularly about an agent's experience in quantum mechanics is to characterize it externally, as an experience of something describable in a more physical language. And then the problems confronted by (such) strategies, (. . .), reappear*." [2], (my emphasis)

This oppositional overture culminates in the following observation: anti-realists and instrumentalists cannot possibly explain quantum effects *outside of the laboratory context*, such as cosmic background radiation, fusion inside of stars, Geiger counters, etc. These clearly violate any attempt to regard quantum states as being 'constructed' within artificial experimental setups and any claims of them merely enjoying an existence dependent on (complementary) measurement arrangements:

> "*Explanations of, say, superconductivity, or the heat capacity of crystals, or the thermodynamic features of the quark-gluon plasma, or the colour of gold, or any of the thousands of concrete applications of quantum theory that form its real empirical base, seem out of reach for QBism, or for pragmatism, at least as they are currently stated*." [2]

As stated above, *if* it is only a 'useful fiction/instrumental device', what is it then that establishes a correspondence to (objective) truthmakers that are clearly beyond human artifacts; in addition: *if* the wavefunction equals an anti-realistic representational placeholder, what is it *in* the physical world that *is represented*, or what is it that the wavefunction corresponds to? QBism in particular intentionally remains vague or silent on these matters. In fact, Wallace claims, and I think rightly so, that by the *parity of (QBist) reasoning*, even objects of classical mechanics better ought to be regarded as non-realist:

> "*(. . .) just as it would be misleading to call classical statistical mechanics non-realist simply because the distribution function does not play a representational role, so would it be misleading to call these approaches to quantum probabilities, as QBist ´s particularly tend to argue, non-realist simply because in those theories the quantum state does not play a representational role either*." [2]

Hence, when applying QBist oeuvre more generally (as actually being undertaken in [12,18]), then one might also claim that it is indeed nonsensical to ask what probabilities in classical mechanics are probabilities *of*. If this strikes one as absurd, then it should also do so in the quantum case.

3.1.3. An Ontology of 'Pure Experience'?

In this spirit, one could polemically (but quite legitimately) ask the QBist, if, when all there is to quantum mechanics are 'calculational devices' in terms of agent-relative experience, this in turn implies that we human agents, who play a rather crucial role according to QBists, actually '*consist*' of calculational devices and/or agent-relative experiences. It is indeed a difficult task to comprehend how a conglomerate of Bayesian patterns (and nothing else!) constitute tables and chairs and, indeed, observers themselves. QBist Bayesian beliefs (and updates thereof), it seems, are in desperate need of truthmakers in order to stay coherent.

The QBist, in response to this challenge, however, seems to be willing to bite the bullet. Indeed, the QBist in fact *does* claim, in some defenses at least, that the world *is* made *purely* of experience (and, presumably, corresponding Bayesian structure thereof). At one place [19], Chris Fuchs seems to flirt with this extreme route by following and quoting William James:

> "*My thesis is that if we start with the supposition that there is only one primal stuff or material in the world, a stuff of which everything is composed, and if we call that stuff 'pure experience', then knowing can easily be explained as a particular sort of relation towards one another into which portions of pure experience may enter. The relation*

itself is a part of pure experience; one of its 'terms' becomes the subject or bearer of the knowledge, the knower, the other becomes the object known" [19], (p. 32)

However, here a follow-up challenge can be brought forth: despite phenomenological leanings to which QBists are obviously committed to, even to such a radical extent as to follow William James' '*Pan-Experientialism*' (PE), which argues that the world is in fact *made* of experience (as the quote from above shows), an unresolved question remains: why is it then that the number of possible experiences seemingly gets *arbitrarily reduced* to only a handful of experiences, when there is no other ontological category (no *non-experience stuff*!) or experience-independent truthmaker that performs the orchestration? This brings us to the following counter-factual claim:

Counterfactual 1.1. *If no reduction or selection happens in this 'possible experience space', then PE collapses into a pan-experientialist variant of MWI (PEMWI).*

The QBist will certainly deny this, but here again, I want to argue that conceptual coherence dictates that the following is, conversely, the case:

Counterfactual 1.2. *If certain experiences are privileged via updating events and/or state reduction, then objective state of affairs, known in terms of hidden-variables, are required to make such a selection reasonable.*

Either way, QBism collapses (into rival objective views) and hence seems conceptually incoherent *in and by itself*.

In fact, it appears then, *even* after implementing MI, MD or PE (each controversial in its own right), QBism either logically implies the existence of *some* form of hidden-variables theory to solve these issues concerning state selection/reduction and/or mind–object correspondences, or, conceptually collapses into a variant of MWI, e.g., PEMWI. However, according to their respective orthodox formulations, any anti-realist interpretation discards any class of hidden-variables *and* MWI likewise. *These assumptions in tandem seem to entail an internal conceptual incoherency in anti-realist views in general.* Hence, the suspicion arises that any stance belonging to this class might be conceptually incoherent.

3.1.4. An Ontology of Pure Information

However, here it is worth noting that some 'reconstructional' information-theoretic approaches to QBism, similar to informational neo-CI views, regard the quantum state as an *information-theoretic* entity [18,20]. This, however, in turn entails an ontic or quasi mind-independent existence such that less, or no priority at all, is assigned to the role of the observer. This alone however does not in any way help with the aforementioned problem of state selection or reduction. Quite to the contrary, a realist take on an 'informational state vector', without any additional hidden variables, seemingly dictates the realness and persistence of the *whole* state-vector. Stronger still, arbitrary reduction may violate the conservation of information, a principle which might naturally accompany all such information-theoretic approaches.

This plot thickens when it is considered that, many MWI advocates, such as David Wallace and Simon Saunders, have Ontic Structural Realist (OSR) leanings for reasons that go beyond the scope of this work (here it should suffice to say, that this appears to many as the 'best of both worlds' in the scientific realist vs. anti-realist debate, see e.g., [21–24] for introductions to and discussions of OSR). However, further conceptual support for the claim of natural affinity between OSR and MWI might come from the heritage of OSR, namely Mathematical Structuralism (MS). According to MS, any mathematical object, a number say, is merely a node in a structure that exists only due to other nodes (and vice versa). It is therefore an affair of mutual ontological dependence, one that requires that all nodes are ontologically on a par (the irreducible, 'primal difference' of binary numbers may be a prototypical example–see e.g., [21] discussing the work of Floridi for details on this point). Likewise, if we transfer this concept to quantum mechanical structures, all states or state-vector components must be interpreted as structural nodes that are ontologically on the same footing. *Conservation of information, together with a stance of capturing information in terms of structural principles of ontological interdependence, seem then to dictate the realness and interdependence of all state vector components* (due to their binary nature, this seems to be of particular concern for qbits). Hence, it follows that any state is equally substantial as any other, exactly what MWI presupposes (as an aside: OSR might foster the plausibility of MWI for yet another reason; if it is granted that elementary particles are nothing but structural relations, then the quest after "what breathes fire into certain equations" - paraphrasing Stephen Hawking´s infamous question - becomes non-sensical. Following the lines of Max Tegmark [25], who in turn got inspired by Wigner´s 'Unreasonable Effectiveness of Mathematics' [26], there is no true distinction between mathematical and wordly structure: both stand in an isomorphic relationship. Similarly, and consistent with the lines of thought of MWI proponents, it would be pointless to ask what breaths fire into the *one* particular quantum state to be actualized. All of them, since all of them are equally real in structure, *are* actualized.)

Though this arguments are certainly controversial, in terms of the underlying *ontology* at the very least, neo-CI, information-theoretic approaches to QBism and OSR come close to being indistinguishable (a point that becomes relevant below). Particularly, Information-Theoretic Structural Realism (ITSR), as defended by Ladyman and Ross [21], may be apt for such a deflationary argument. However, there are more reasons for a deflation, which will become obvious in a moment. The crucial take away message of this section is however the following: if the underlying ontology is regarded as informational – if the state vector is regarded as informational without postulating further principles, structures or mechanisms regarding *state reduction*, then the principle of conservation of information, if nothing else, prohibits, some *arbitrary* state reduction. *Then, despite of being labeled QBist or neo-CI, a MWI treatment of the state vector follows necessarily.*

3.1.5. A Trilemma for the Anti-Realist

The whole situation can be formulated and reduced to a trilemma of three mutually incompatible counterfactuals, whereas prima facie, only one of them can be true:

Counterfactual 2.1. *If quantum mechanics is only a mind-dependent calculational device in terms of subjective Bayesian patterns and experiences, and since no further class of structural or non-structural entities are involved as constituent elements in the world ´s furniture, then full blown PE has necessarily to be accepted, such that reality is purely experiential and the whole possibility space of experiences is ontologically on a par.*

Argument I.

AI.1. QM entities are mind-dependent Bayesian structures

$$(\mathrm{QMx} \rightarrow \mathrm{Bx}) \tag{1}$$

AI.2. All physical objects are QM

$$(\forall \mathrm{x}\ \mathrm{QMx}) \tag{2}$$

AI.C. *Conclusion*: the physical world utterly consists of Bayesian structures. (*AI.1. & AI.2.*)

$$(\forall \mathrm{x}\ \mathrm{Bx}) \tag{3}$$

Now, after adding QBist 'PE assumptions', it can furthermore be argued:

AI.3. No Bayesian structure/experience is *privileged or in any way selected without additional ontology or principles*, i.e., there is no distinction between manifest/unmanifest experience.

$$(\forall \mathrm{x}\ \nexists \mathrm{y}\ \mathrm{Bx} \wedge \mathrm{My} \wedge \neg \mathrm{By}) \tag{4}$$

AI.C2. *Conclusion*: all Bayesian belief- or 'experiential' structures, that is, all components of the state-vector according to QBism, exist on a par and comprise the sole ontological furniture of reality.

Let us label this stance accordingly *Pan-Experientialist MWI* (PEMWI).

Counterfactual 2.2. *If quantum mechanical states are informational and real (mind independent) entities, and since no further class of structural or non-structural entity is involved as a constituent element in the world´s furniture, then some form of Informational Monism or OSR follows. This position, however, might, without adding a dualistic mind or hidden variables that cause state selection, similarly collapse into a version of MWI. Furthermore, arbitrary state reduction would violate the principle of conservation of information.*

Argument II.

AII.1. QM is all informational/structural.

$$(\mathrm{QMx} \rightarrow \mathrm{Ix}) \tag{5}$$

AII.2. The physical world is comprised of no further (physical or mental) structural or non-structural entities, and no element of this structure is ontologically privileged.

$$(\forall \mathrm{x}\ \nexists \mathrm{y}\ \mathrm{Ix} \wedge \mathrm{My} \wedge \neg \mathrm{Iy}) \tag{6}$$

AII.C. *Conclusion*: QM is informational and can be taken as 'OSRist MWI' (OSR–MWI).

Counterfactual 2.3. *If quantum mechanics is a calculational device that merely represents the mind-independent structure incompletely, then some hidden-variable theory necessarily must be taken as true.*

Argument III.

A.III.1. QM is mind-dependent representational structure.

$$(\mathrm{QMx} \rightarrow \mathrm{Rx}) \tag{7}$$

A.III.2. QM is an *incomplete* representation, such that next to the represented structure, further ontic-structural or non-structural entities necessarily exist.

$$(\forall \mathrm{x}\ \exists \mathrm{y}\ \mathrm{Rx} \wedge \mathrm{Hy} \wedge \neg \mathrm{Ry}) \tag{8}$$

A.III.C. *Conclusion*: Other mind-independent structures, i.e., hidden-variables, exist.

Hence, it seems the proposition can be made that any anti-realist position *either collapses into a realist hidden-variable view or into a version of MWI, or is conceptually incoherent.* From a purely logical point of view, there seems to be no further option left.

3.1.6. Anti-Realist Interpretations: Preliminary Conclusion

The suggestion being made in this section is that even epistemic interpretations either require some ontological explanans in order to explain either observer–object links, hidden variables causing a state selection/reduction, or, an ontological explanans of which the wavefunction is a *complete* representation of; however, this in turn implies that an ontological or realist interpretation sneaks in through the backdoor at any rate.

As hinted above, however, an apparent loophole might be the proposal that quantum information *itself* plays the role of the truthmaker, such that ontological fundamental status is assigned *to the representational structure itself* (Counterfactual 2.2). However, then, the view culminates into one involving quasi objective truthmakers: if one follows this information-theoretic approach to its logical extreme, one might end up with a form of OSR or ITSR. Furthermore, as argued before, in this scenario also, removing some state vector components of the information-theoretic structure in 'updating events' while preserving others, seems ad hoc. In contrast, an ontological egalitarian co-existence of all state-vector components appears to be more natural within such 'Informational Monism'. A fortiori, an arbitrary state reduction would violate the *conservation of information*, a principle that might be all the more relevant given the presupposition of a *pure* information-theoretic ontology.

By the same token, if *everything* is regarded as informational, then *any* distinction between *possible* and *actualized* states cannot plausible be drawn without adding any additional hidden variables as selecting principles. Without this additional step, any eigenstate of an informational Ψ is equally 'real' as any other and stands on the same ontological footing, without any 'asymmetry of realness' whatsoever. An ontology follows in which no part of a wavefunction is in any way ontologically privileged. The distinction of MWI then seemingly becomes weaker, if not downright deflated.

As a consequence, such prima facie 'anti-realist' informational interpretations might not only collapse into OSR, but ultimately also into MWI. Let us label the resulting view OSR–MWI. Furthermore, as mentioned above, given that defenders of MWI very often rely one OSR ontology to begin with, OSR–MWI may turn out to be also indistinguishable from 'ordinary' MWI.

However, there is more. Given that QBism suggests Bayesian beliefs being coupled to pure experiences which are also taken to be informational, the distinction between AI.C2 and AII.C also becomes vague if not negligible. As a consequence, if reality is indeed a pure 'experience space' (as Chris Fuchs suggests), then mind-dependence also becomes vacuous: if a *whole range* of experiences exist (which follows necessarily when equating pure experience with the quantum-state and nothing more), multiple corresponding observers exist as well, given that they are themselves to be taken as *subsets* of an all-encompassing 'set' of experience (recall the William James quote above). What then follows is a mind-independent *range of experiences with varying 'amplitudes'* that, like before, without any selection or reduction principles, are on a par in terms of reality (principles or entities which would, recall, be desperately needed to create a distinction between 'potential' and 'actualized' experience).

In other words, both the 'object' *and* 'subject' pole are then, according to this view, encoded in experience, such that the former is not in any way transcending the latter. And not only is it then encoded in experience, but multiple copies of it are encoded, due to the ruled out, *in*-egalitarian existence of state-vector components.

Hence, when formulating experience in purely structural or information-theoretic terms, (which is, as the QBist herself seems to be willing to accept as the only reasonable way to capture experience in scientific terms, the distinction between AI.C2 and AII.C evaporates completely.

It is time to wrap up the preliminary results gained so far:

i. Ad. Counterfactual 2.1.: PE entails that reality is comprised entirely of Bayesian belief structures coupled to pure experience such that no structure is ontologically privileged or in some way selected.
ii. Ad. Counterfactual 2.2.: Information theoretic 'anti-realist' (e.g., informational QBist or neo-CI) interpretations have ultimately to be understood in terms of OSR such that they themselves in fact comprise an *ontic* structure of reality. Without adding mind-induced collapses or further hidden variables for state reduction or selection, thus having an egalitarian outlook at all possible eigenstates, these views collapse into OSR–MWI. The principle of conservation of information furthermore prohibits any arbitrary state-reduction.
iii. Ad. AI.C2 and AII.C: The difference between a Bayesian structure (without additional ontology) and an information-theoretic ontology becomes negligible. Hence OSR–MWI~PEMWI

iv. Given that many defenders of MWI very often have OSR leanings, it might ultimately also hold that OSR–MWI~PEMWI~MWI.

v. Ad. Counterfactual 2.3.: Bayesian belief structures either require objective truth-makers and mind-independent mechanisms for state reduction or selection, which are themselves hidden variables, or, are structurally complete. If the former, hidden variables exist; if the latter, then it is as elaborated above, i.e., QBism → PEMWI~OSR–MWI~MWI.

Hence, a first preliminary result of this analysis is that, either way, a realist interpretation (either hidden variables or MWI) is necessary to solve this interpretational issue, a conclusion which, if correct, already critically narrows the field of possible interpretations.

Similarly to what has been discussed by Dürr and Lazarovici [14] (Section 2.2 of ref. [14]), any attempt to solve the dilemma of the measurement problem basically leaves us, after having discarded conventional anti-realist options as conceptually incoherent, with two remaining options: Either the formulation is

(a) *empirically adequate, but in some sense, nomologically incomplete or*
(b) *empirically adequate and nomological complete.*

Hence, remaining agnostic about option (b) (completeness) for the moment, we should have a closer look at (a), assuming hidden variables.

However, before investigating the potential of hidden-variable theories, being this subsection´s conclusion only remaining alternative to MWI, let us first make a detour and inspect Carlo Rovelli´s Relational Quantum Mechanics (RQM) more closely. Due to regarding relations between the observer and observed system as crucial, it seems natural to discuss it right after QBism. However, it has a special status, for it neither falls within the domain of anti-realist interpretations, hidden-variable theories nor, presumably, within MWI. However, in the subsequent subsection, I will argue, similarly to the results gained in this subsection, that the latter better ought to be the case.

3.2. Rovelli´s Relational Interpretation—MWI in Disguise?

In this subsection, I want to take a closer look at RQM. In order to provide a short introduction, I will, for reasons of adequacy and efficiency, directly quote Carlo Rovelli´s own words:

> "RQM is based on an ontology given by physical systems described by physical variables, as in classical mechanics. The difference with classical mechanics is that (a) *variables take value only at interactions* and (b) *the values they take are only* relative *to the (other) system affected by the interaction*. Here "relative" is in the same sense in which velocity is a property of a system *relative* to another system in classical mechanics (*as opposed to "subjective*"). The world is therefore described by RQM as an evolving network of sparse relative *events*, described by punctual relative values of physical variables." [27], (emphasis & addition in brackets added)

> Furthermore, Laudisa and Rovelli emphasize the following:

> "*the interference observed by a system* S' *is not erased by the actualization of variables relative to a different system S*"". [27]

At this point already, I must object: are not such dissimilar states, observed by S' and S", as proposed by Rovelli, necessarily *disparate realities* and hence, *many worlds in disguise*? In this subsection, I thus want to argue for the following dilemma:

Counterfactual 3. *If the contrary is true, that is, two different observers agree on a quantum state such that its observed value is observer-independent, then it cannot be intrinsically relational.*

In other words, I want to make the following case discrimination, which can be taken as two horns of the same dilemma for defenders of RQM:

(a) either they are giving up the relational aspect of RQM, or,
(b) they too are bound to accept MWI.

If (a), then the observed state is non-relational and hence the view might be reducible to some variant of objective-collapse hidden-variable theory such that state reductions happen unaffected by the relations of the physical interactions between the observer and observed, thereby making the name-giving notion '*relational*' redundant. A recent work by Lawrence, Markiewicz and Zukowski [28] seems to support this first horn of the dilemma by stating that (i.) RQM is not merely an interpretation but a new theory and (ii.) that hidden variables occur in RQM: "*relative facts asserted by RQM are either a void concept, or form a direct contradiction with quantum mechanical predictions*", given that "*if an effectively complementary measurement is done by [S″, after measurement by S′ on S has been performed, variables] are algebraically equivalent to non-contextual hidden variables*" [28], (my addition).

At any rate, this is not how RQM is treated and it would render the notion itself inconsequent and even contradictory. RQM clearly states that two different observers, or interacting subsystems, perceive different experimental outcomes when interacting with a third subsystem. After all, Rovelli himself coined the following phrase:

> "*Different observers can give different accounts of the same set of events*". [27]

Hence, by reductio, if (b), then one seems to be bound to—in order to really and uncompromisingly account for the relational aspect of quantum measurement—also be committed to a (parallel) multiplicity of observed states and hence to a multiplicity of 'branches' (relative to observers). This clarified definition of RQM, as a consequence, might ultimately be phraseable in the following way:

> *The particular conjunction of variables an agent observes exists relative to the sum of all her physical interactions, i.e., to the whole web of physical relations involved. The latter, in turn, selects definite values for each quantum system that an interaction has occurred with. However, this sum total is not unique given that different 'webs of variable values' occur for different interacting systems. Furthermore, given that such web of objective physical interactions behave similar to a spreading entanglement (Rovelli uses the phrase of "an evolving network of sparse relative* events"), *it seems ultimately conceptually no different from a decoherence-induced emergent branch as according to MWI.*

In a sense then RQM might be nothing over and above a reverse-engineered notion of decoherence-based branching. What is more, given that I myself am the object of other observations/interactions, multiple versions of myself necessarily exist if the RQM is consistent and true; these are then alternate versions to which my *particular* self-observation has no access to.

Even Rovelli himself admits the following at one point:

> "*Understood in this manner the quantum state is always and only a* relative state *in the sense of Everett. In this sense RQM is "Everettian"; it is so in a different sense than the Many Worlds interpretations, which are based on a realistic interpretation of the universal wave function, rejected in RQM.*". [27]

The last statement requires further elaboration which leads to another fine-grained distinction: if Rovelli chooses to discard only a *universal* but not *local* realist wavefunctions, RQM requires something akin to objective collapse, hence also the inclusion of hidden variables which would lead to same incoherent state of affairs as discussed above.

If on the other hand, this 'denial' of the universal wavefunction is to be understood as challenging the realist status of the wavefunction *per se*, then also, formerly discussed challenges re-emerge, for this would contradict Rovelli´s own introductory notes, in which he clearly emphasizes that RQM should *not* be understood as relational in the 'anti-realist' or 'mind-dependent' sense, but as similar to *relationalism* in special relativity: it is *objectively* relational, namely relative to *frames of reference*, which however implies that a whole spectrum of possible values exist in the realist sense. The only remaining logical option for a mind independent relative state interpretation, seems then to be one that involves an egalitarian outlook or co-existence of all states.

Simon Saunders [29] likewise defends a relative state interpretation, but contrary to Rovelli, *his* interpretation of relational states does not deny the implication of 'parallel realism'. Saunders compares this to the tenseless block universe, using the latter as analogy. For a start, inasmuch as the notion of the *now* is indexical, different *nows* do exist. Similarly, a relative state does not neglect the co-existence of different *actualities*. Or, Saunder's states the following in his own words:

> "*(...) the interpretation had better not introduce a notion of privilege for one domain over another, in anything more than an interest-relative sense. Again, there is an analogy in the case of time: if we are to provide an interpretation of the "flow" of time, consistent with a relational account of tense, then it had better not lead to any "absolute" significance of one space-time foliation over another; and conversely, if we do have the latter, then there is no sense to the appeal to anthropocentric factors*." [29]

According to the relative state interpretation defended by Saunders, the locally observed state of the wavefunction can be regarded as something akin to an 'actuality slice', with its locally observed values depending on the observer´s own relative state with respect to that of the quantum state to be measured, which, in turn, can be translated to the particular web of relational interactions that one is entangled with, according to RQM. Therefore, when Rovelli talks of relative states, he has to bear in mind that when different interacting subsystems allow *different* physical variables to emerge relative to one particular observed subsystem, then this is almost synonymous to the existence of a multitude of 'actuality slices', each of them relative to observer -frames of references, - 'carved' out of a 'block *multiverse'.* Different slices (which can, as we saw, in this context interchangeably be used with branches) then correspond to different, but equally real, webs of relational interactions and variables thereof. Interestingly, Carlo Rovelli himself acknowledges this, while presumably not the global consequence it entails:

"[T]he state of the cat *with respect to* the external world does *not* collapse when *a part* of the cat interact *with another*." [27].

In other words, it seems that RQM entails the fact that we must acknowledge that there is a different actuality relative to the cat than that relative to other potential observers in its surrounding world. Since such differences can be as radical as being alive vs. being dead, RQM seems to be bound to accept different genuine *realities.* When it does follow from RQM that the cat is dead for Wigner, but not for his friend, then it unavoidably states a multiplicity of realities, or branches, for that matter.

In his delightful book '*Helgoland*' [30], Rovelli however explicitly tries to circumferent this consequence: "*Prima facie, RQM may seem to imply a form of perspective solipsism, as the values of variables realized in the perspective of some system S' are not necessarily the same as those realized with respect to another system S". This is however not the case, as follows directly from quantum theory itself. The key is to observe that any physical comparison is itself a quantum interaction. Suppose the variable E of S is measured by S' and stored into the variable Z of S'. This means that the interaction has created a correlation between E and Z. In turn, this means that a third system measuring E and Z will certainly find consistent values. That is: the perspectives of S' and S" agree on this regard, and this can be checked in a physical interaction.*".

Rovelli labeled this preservation of intersubjectivity 'Cross-Perspective Link'. A recent detailed critique of this purported "fix" can however be found in [31] by Lahti and Pellonpää.

They respond that "*this is a new independent assumption and it appears to be incompatible with the preceding ideas trying to exhibit the assumption (of RQM)*" and "*without assuming that the postulate of cross-perspective links holds also in this case, the conclusion that we all 'see the same world' is still unjustified.*" [31].

Hence, it seemingly follows that *either* RQM is not truly relational if it tries to recover a one-world picture: a particular relational value selected by S (perhaps via self-interaction) then holds *globally*. However, this is not then truly selected 'relationally', but in a manner of objective (agreeable) collapse, thus as a non-relational hidden variable for the whole world. Or, *if* it remains to stays true to the original RQM assumptions, 'one world' cannot possibly follow.

The crucial point which must, I think, be stressed over and over again, however, is this: if Rovelli denies the realism of other possible relational states, then his whole view appears to collapse into a non-relational one and hence becomes redundant at best and incoherent at worst.

When putting the discussion of this section in an argument-conclusion form, we obtain the following:

Argument IV.

AIV.1. According to RQM, physical structure is a substantial and realized structure of *interrelated* physical properties ('facts') and their respective definite variables.

AIV.2. Due to the nature of RQM, more than one coherent network of physical definite variables (due to density matrices) of interacting objects exist; *outcomes would not be relational, but would be guided by hidden variables otherwise*.

AIV.3. Any such '*evolving network of sparse, relative events*' is equivalent to a branch of decoherence-based MWI as physical interactions are, for all practical purposes, restricted to non-decohered domains. In addition, according to both views, in principle, all permutations of variable values and correlations are possible, which is synonymous with the existence of multiple branches.

AIV.4. *If* one such network is physically privileged, RQM would no longer be *relational* [28], but would involve hidden variables instead. RQM would be conceptually or even logically inconsistent ($R \wedge \neg R$ -contradiction).

AIV.C *Conclusion*: RQM collapses into MWI.

Proof Sketch.

$$(\text{RQM} \rightarrow \text{MWI}) \vee (\text{RQM} \rightarrow \text{HV}) \tag{9}$$

$$(\text{RQM} \rightarrow \text{HV}) \rightarrow (\text{RQM} \wedge \neg\, \text{RQM}) \text{ (Contradiction)} \tag{10}$$

$$\text{RQM} \rightarrow \text{MWI}. \quad \square \tag{11}$$

After having discarded RQM as either conceptually incoherent or as MWI-in-disguise, let us now, in this final round of conceptual analysis, inspect one remaining alternative group of interpretations, namely hidden-variable theories; this is the option that we also identified as one of the two remaining viable alternatives to Anti-Realist Interpretations in Section 3.1.

3.3. Bohmian Mechanics (BM) and Objective-Collapse Theories (OCT)

3.3.1. Introducing BM and OCT

Both Bohmian Mechanics (BM) [7] and Objective Collapse Theories (OCT) [8] share the common theme of postulating one way or another an objective and real mechanism that constitutes localized particle dynamics (see e.g., [32] for discussion). Both theories only differ in the way they try to accomplish this. In the case of the latter, however, the 'collapse of the wave-function' is regarded as a real occurring, physical substantial, quasi mechanical process, one that can be regarded as a combination of deterministic and stochastic hidden variables. Objective collapse theories (OCT), such as the Ghirardi–Rimini–Weber (GRW) Theory, which is its most discussed example in the literature, take collapses as physical events, from which highly confined particle-like patterns emerge. However, how this works out in detail depends on a further sub-distinction (see e.g., [9,14]): GRWf uses a so-called *flash ontology*. Here, particles are understood as instantaneous 'flashes' and the wavefunction represents the probability of where they occur stochastically. In contrast, GRWm regards the wavefunction as a physical substantial distribution in spacetime, - much like a continuum, representing matter density. Thus, in this picture, the collapse can quite vividly be understood as a *contraction* of a physical medium. However, either way, the ontic existence of the wavefunction seems to be required, either in the form of mass density or as something that provides physical grounds for flashes. Wallace likewise claims the following: "*For collapse theorists, the wavefunction is a physical entity*." [33].

In contrast to both, BM basically can be taken as an even stronger attempt to bring back a classical way of thinking and tries to accomplish this via hidden-variables qua hidden particle *trajectories*. In an attempt to both 'save' the (classical) wave *and* (classical) particle phenomena and by that, allegedly choosing a concept "free of paradoxes", the idea emerged that there exists *both* a physical real particle *and* a wave, whereby the former kind of "surfs" on the latter, which in the theory, is labeled accordingly as the '*pilot wave*'. Hence, similar to classical ideas we are used to, there is a discrete particle following the real trajectories; the former, however, in our current understanding, is the *only* thing to be measured. Then, there is no such thing as a wavefunction collapse: indeed, the wave neither collapses nor is measured directly, but is only *indirectly* observed, by affecting, for instance, the probability distribution of where a photon or electron hits a screen.

3.3.2. General Challenges

The most severe objections this subgroup of theories is facing might be that they focus on and revolve too much around ordinary waves and particles 'living' in a (often) non-relativistic spacetime. However, the wavefunction as a extended spatial object is only a special case of a much more broad and abstract concept, according to which the wavefunction exists in Hilbertspace; this is something that might turn out to be the greatest weakness of both approaches: both BM and GRW seem to *require* a physical, spatially extended form of the wavefunction in spacetime (or within configuration space in a derivative sense); this is a semi-classical way of thinking that seemingly rests on outdated beliefs, more than anything else. Further still, they are mainly discussed in non-relativistic contexts, as put by Wallace:

> "*(...) the way Bohmian mechanics, and GRW theory, are normally discussed in philosophy of physics (especially in more metaphysical contexts) is sharply at odds with the relatively humble role non-relativistic particle mechanics plays in real quantum theory. The only way I know to make sense of (most of) this literature is to interpret it as discussing non-relativistic quantum particle mechanics under the fiction that it is a fundamental and universal theory.*". [2], (p. 43)

However, in [14], (p. 115) on the other hand, it is stated that at least GRWf indeed "*can be generalized to relativistic spacetime without violating any principles of relativity*" and similar attempts exist for BM.

Still, Wallace legitimately claims that such theories, which aim at *modifying* the QM formalism (such as BM and GRW), always only account for *one application* of quantum theory *but rarely for all of them*, while MWI´s wide-ranging applicability extends to practically all QM tools and applied contexts.

Further received objections, concerning BM in particular, are related to the assessment that a real physical wave acts on a particle, *but not vice versa*. It might seem reasonable to detect non-linearity or some form of feedback loop between both entities. However, such non-linear effects so far have not been observed [7] (though it might be fair to admit that the confirmation of such deviation from linear dynamics is technically challenging at best and empirically unverifiable at worst, given that the effects may be subtle and hard to separate from environmental noise). In addition, if the wavefunction is a physically *real* object in the classical sense, then some measurable interaction between it and the surrounding matter should likewise be detectable, very much like measurable nonlinear disturbances of a classical field or fluid, which, again, is not what has so far been detected.

A highly relevant objection against BM, mostly stemming from MWI defenders, is the following: if the pilot wave acts only as 'particle carrier' at one particular trajectory or spatial eigenstate, then what happens to the rest of the non-collapsing (enormous and supposedly universal) wave function? [7] This becomes particularly relevant in the macro realm: does BM propose whole distinct world-like branches that are simply 'empty'? That is why David Deutsch coined the phrase that BM is

> "*parallel-universe theories in a state of chronic denial*". [34], (p. 225)

Due to environmental-induced decoherence, which is also relevant to such real 'carrier' wave which can be understood as a quasi-spacetime-state realist wavefunction, the totality of empty components would then constitute a structure similar to 'empty' branching worlds; this is, however, only in terms of wave structure, while being devoid of particle 'content'. Simon Saunders elaborates this at [35]. In order to avoid this, the Bohmian would be at pains to add an OCT-like process, thus dropping 'empty' waves from the guidance equation as some sort of *quasi state-reduction*. Given that ordinary BM is already technical challenging, this would blow up the required calculational apparatus beyond reasonable dimensions.

Interestingly, the same objection can also be brought forth against OCTs: here, as well, given that the Schrödinger wave is realistically interpreted in most versions, the problem of 'empty' parts (i.e., free of 'contractions' or 'flashes') of the wavefunction persists. For instance, GRWm involves stochastic processes that transform a spread wavefunction in space into a localized Gaussian shape (by multiplying it with a Gaussian function), something which involves the formulation of a non-linear version of the Schrödinger equation. However, this process then still exhibit non-vanishing (relative) amplitudes outside of the collapsing region, known as the so called "*problem of tails*" (see [8,35]). Given that OCT wavefunctions are very often taken as physically substantial, such tails should not only be measurable in principle, but, due to their realist status, as before, should also seemingly lead to 'empty branches' [35] (here, replacing the continuous with a spatially discretized, i.e., cellular automata-like formulation of GRW or BM, might perhaps be legitimate attempt to get rid of such non-vanishing amplitudes and empty-branches. However, this might still be of no help to the challenges to be discussed in the next subsection).

However, one may suspect some further interpretational issues: first of all, how is such an objective collapse (or 'flash') in GRWf qualitatively conceptualized to begin with? What is the nature of such a 'flash' and how is it in turn ontologically related to the wavefunction and its amplitude? Or, in the case of GRWm, should we really imagine it, in a loose analogy, to be similar to a field or field-like medium that 'contracts' eventually?

In '*On the Common Structure of Bohmian Mechanics and the Ghirardi–Rimini–Weber Theory*' [9], exactly this is suggested:

> "*GRWm is a theory about the behavior of a field m(·,t) on three-dimensional space. The microscopic description of reality provided by the matter density field m(·,t) is not particle-like but instead continuous, in contrast to the particle ontology of BM. This is reminiscent of Schrodinger's early view of the wave ¨function as representing a continuous matter field. But while Schrodinger was obliged to abandon his early view because of the tendency of the wave function to spread, the spontaneous wave function collapses built into the GRW theory tend to localize the wave function, thus counteracting this tendency and overcoming the problem*."

However, here in particular, the question will arise as to what sort of law establishes such repeated alternations between the contraction and expansion of mass density. Although thermodynamics usually do not play a significant role in microphysical happenings, such a reversal of the spreading event is seemingly at odds with the second law of thermodynamics. One might also object: in the case of interference patterns such as in the double-slit experiment, how would such a physical interfering wave pattern, consisting of *alternating* amplitudes, *contract as whole*, and what is it that makes the locus of such contraction more likely in a region with high amplitude? One might respond that the question is ill-formed as it is simply the theory. However, given that dissatisfaction with the ad hoc nature of the original collapse postulation is what motivated the conception of hidden-variable theories in the first place, one might, by parity of reasoning, also demand a sufficient reason for this state of affairs. Besides, in the very same double-slit setup, what is it that conserves the effective particle number and quantization? Why would further contractions not suddenly occur within the same wavefunction, given their stochastic nature, such that one electron turns into several? Why does the process preserve particle characteristics *precisely*? All of this seems to be conceptually opaque.

Similarly, in the case of GRWf, it seems implausible that flashes are rigorously quantized in a way that saves the observed well-defined particle properties. In such a stochastic process of random 'lighting ups', randomness *also* in terms of particle properties, rather than conserved symmetries, might be expectable. Wallace likewise states that

> "even in the non-relativistic domain [GRW] is not fully satisfactory: manifestly, the collapse mechanism does not preserve the symmetries of the wavefunction, and so *it is not compatible with the existence of identical particles*". [33], (p. 42, my emphasis)

3.3.3. QFT and Particle Indiscernibility as Master Arguments against BM and OCTs

The problems culminate when finally taking Quantum Field Theory (QFT) into account. Wallace states that challenges concerning OCT/GRW and BM become especially severe when one tries to reconcile both BM and OCTs with the standard model of particle physics or QFT:

> "*(I)t is much harder than is generally recognized to construct a quantum-field-theory version of Bohmian mechanics or GRW theory and so confidence that such a theory even exists i[s] premature, because most of the features of nonrelativistic quantum theory appealed-to by metaphysicians of quantum mechanics are emergent approximations at best in QFT*." [2], (p. 19)

This should be taken as the most severe blow against OCT and BM interpretation brought forth so far. For both BM and GRW, it is part and parcel to assume particles as something to be understood in the classical, *spatially confined*, sense, or at least in its proximity: if they are not regarded as localized, clear-cut separated entities, then they are at least regarded as localized 'bumps' in a field. However, modern findings in QFT seem to shatter not only the former, but even the latter weaker notion of particles [36]. Dürr and Lazarovici [14] state the following:

> "*one might think that a field configuration would represent a particle configuration in some way, e.g., by distinguished "bump configurations" in the field. But that does not work out*."

The hope might remain that such a quasi-classical picture of field configurations might at least work out for bosons:

> "*Fermions are not conducive to a naïve field ontology, while bosons are*" [14]

A hope that eventually becomes shattered too:

> "*(...) bosons are commonly viewed as particles. For example, think of photons, the quanta of electromagnetic fields. A first thought might once again be that we should "see" the bosons in the field configuration as "bumps" in the field. But that is also more or less impossible*." [14]

This might indeed be the most devastating blow that both BM and OCTs can receive, since being interpretations that remain loyal to picturing particles as localized entities is what motivated their conception in the first place. Wallace puts it in the following way:

> "*so a fundamental ontology based on the positions of particles looks forlorn in quantum field theory*." [37], (p. 5)

Hence, what particles *are* is then presumably nothing over and above Fourier modes or 'excitations of quantum fields', something which can, by and large, be regarded as a received view within the physics community. This, in turn, leads to yet another argument, namely for the ultimately structural nature of particles. Ladyman and Ross claim the following:

> "*OSR agrees with Cassirer that the field is nothing but structure*." [21], (p. 153)

In the same vein, Simon Saunders [36], (p. 305) holds that

> "*coincidences of field values, and complexes of relations among them—(...) is a world understood in terms of structural descriptions, a world as graph, not a collection of things that evolve in time*."

And that

> "*in strongly interacting high-energy physics, it is doubtful that objects as individuated (using the Principle of Indiscernibles) by the invariant properties and relations definable in quantum field theory will be quanta at all*."

Such a state of affairs however would render a well localized particle ontology as BM and OCT require highly implausible, if not impossible.

Due to q-numbered (or operator valued) fields and the second quantization of QFT, even the particle number (and thereby particle *existence*) is equivocal in terms of being in a superposition. This, prima facie, violates the picture of a discrete and stable localized particle within a Bohmian guidance wave.

It is, however, fair to say that there *are* attempts to reconcile QFT and BM, such as the one given in '*A persistent particle ontology for QFT in terms of the Dirac Sea*' [38].

However, three prima facie objections can be launched against this particular approach:

1. The conception only works for fermions—bosons, are still regarded as field-like all space-pervading entities.

2. In [38], it is is stated that "*particles are primitive objects in the sense that they only have a position in space. All the other parameters including mass, charge, spin, etc. are not additional elements of the ontology characterizing the particles, but dynamical parameters employed to describe the evolution of the particle positions.*" It seems, then, that all the relevant physical characteristics of the fermions, save position, are to be found in their anti-symmetric wavefunction. A similar observation is made by Saunders and phrased in the following question:

> "*don't supposedly intrinsic properties of Bohmian particles like charge or mass (both gravitational and inertial mass) act, in experimental contexts, as if associated with the pilot wave rather than the particles?*" [35]

However, prioritizing the wavefunction that way seems to eradicate the difference between a pilot-wave and a spacetime state realist take of the wavefunction [39], and may render the particle trajectory for all practical and empirical purposes physically superfluous.

3. This 'Bohmian Dirac Sea' model only works reasonably well for high-energy cut-offs: it is doubtful that one can recover unequivocal Bohmian trajectories without them. Rather, spacetime regions are then to be taken as tightly 'occupied' such that, again, the distinction between a pilot- and an ontic (non-guidance) wavefunction seemingly becomes small (conversely: a MWI *lattice*–QFT approach makes the quantum fields 'grainy' such that, as a result, both a Bohmian and Everettian lattice–QFT model may become indistinguishable at a certain limit).

At any rate, when considering the fact that well localized particles and unequivocal particle numbers at a certain spacetime region are themselves non-fundamental, then no spatial component of a pilot wave can truly be regarded as precisely empty. It seems then, when factoring in QFT, BM becomes not just 'MWI in chronic denial', but rather MWI "in disguise" or indeed, MWI *itself*. That being - not just *any* version of MWI, but an explicitly decoherence-based MWI, given that what then *does* allow for the emergence of localized particles is then, presumably also, decoherence (this may perhaps also amount to a version of BM in which 'all possible initial conditions' are simultaneously realized).

The same state of affairs also seems to be conceptually challenging for any OCT, as such collapses are usually taken to account for unequivocal particle localizations and, thereby, numbers. The latter, however, as above, are better be regarded as an approximation and special case rather than the norm, -no serious interpretation or theory should solely focus on limiting case scenarios. For instance, when, in GRWf, well-localized flashes qua particles are neither well-defined nor well-localized but rather themselves subject to the 2nd quantization, then, here as well, flashes become, due to operator-valued fields, not clearly distinguishable. Here, it also then seems that, as in the case of BM, -if all position eigenstates are not precisely empty, the distinction from a MWI-compatible spacetime state realist wavefunction [39] seems to become small, if not negligible (another option for recovering compatibility might be to assume OCT or GRW collapses to be identical with vacuum fluctuations. However, then also the distinction to MWI evaporates, for then only at low QFT energies *and only after* decoherence phenomenologically distinguishable particles arise from a resulting n-particle QM).

Finally, the following remark could be made about *any* interpretation or modification of QM that assumes some or other hidden determinism: indeed, the whole argument of this subsection can be generalized such as to affect other classes of modal interpretations or hidden-variable theories like Superdeterminism [40], Retrocausality [41], or 'Contextual Collapse' [42] interpretations: if applying any of these hidden determinates to QFT, it seems that, similar to the critical remarks on [38], it will be still necessary to regard *all* spatial components of the wavefunction as physically substantial, thus leading into spacetime state realism and thus to decoherence-based branching eventually (however, investigating this further has to wait for another occasion).

The result gained in this subsection can be summarized in the following argument–conclusion form (for the sake of the argument and reasons of simplicity, I restrict myself to spacetime state realism. However, the argument might work just as well when assuming Hilbertspace realism such that everything is part of the Hilbertspace, and no part is ontologically privileged):

Argument V.

AV.1. According to BM and OCT, some spacetime regions are ontologically privileged (being occupied by particles). Hence, for all field points in spacetime, *some* are occupied by particles.

$$(\forall x\ \exists y\ Fx \wedge Py) \tag{12}$$

AV.2. According to MWI, *no* spacetime region is ontologically privileged. The universal spacetime state realist wavefunction has a value at every point in spacetime and nothing is not part of the universal spacetime state realist wavefunction.

$$(\forall x\ \neg\exists y\ Ux \wedge Py \wedge \neg Uy) \tag{13}$$

AV.3. According to standard QFT, no spacetime region is ontologically privileged. The Q-fields have, Fock-space formulations notwithstanding, a value at every point in *spacetime* and nothing in spacetime is not part of any Q-field.

$$(\forall x\ \neg\exists y\ Qx \wedge Py \wedge \neg Qy) \tag{14}$$

AV.C. *Conclusion*: while the universal wavefunction is not identical to Q-fields, both are spatial field-like entities and structurally similar.

QFT and MWI ontology hence seem to be more straightforwardly reconcilable than QFT and OCT/BM ontology, particularly when considering a *wave functional interpretation* of the former.

Finally, non-separability equally harms an ontology of classical fields and particles, as the latter rather belongs to an outdated ontology of monadic intrinsic objects and properties (see [43–46] for discussion)

Wallace elaborates this in the following way:

"*Chris Timpson and I Wallace (. . .) regard this as a major failure of Lewis's doctrine of Humean supervenience, the doctrine that all facts about the world supervene on monadic properties of spacetime points and the spacetime relations between them: in our view, the entanglement between (say) spacetime regions A and B should be understood precisely as encoding certain irreducible relations between A and B*." [17], (p. 17)

Despite the fact that both BM and OCTs are necessarily taken as non-local, the conclusion is rarely drawn in terms of the consequences for its presupposed particle ontology. Though debatable, it very much seems as if such irreducible relations in and by themselves already contradict classical particle and field ontologies as they are found in the ontological inventory of GRW and BM. Given that non-separability suggests that holistic entities are irreducible, it follows that extended objects such as the wavefunction, or indeed the universal wavefunction, is ultimately not reducible to point-like particles. Hence, when factoring in this assessment, a universal Ψ must, at any rate, be more than a mere *carrier* wave but rather an ontic entity to be *prioritized*; after taking this into account, BM and OCT ontologies may conceptually collapse into an ontic wavefunction ontology that is taken as substantial and *complete*, akin to that of spacetime state realism.

Finally, for obvious reasons, any interpretation that relies on pilot waves or collapses *within* spacetime is unsuited for theories of quantum gravity or 'emergent spacetime', which poses a severe limitation for future research in terms of unification [47].

After having, hopefully in a systematic and heuristically sound way, shown that anti-realist/instrumentalist, RQM and hidden-variable approaches either face conceptual challenges or collapse themselves into the bare formalism (to be taken as complete), we finally want to investigate what remains and why this alone suffices for MWI to be true; this is, the bare QM framework, from which, under the assumption of universal, unrestricted application, environmental-induced decoherence naturally follows, from which a branching structure naturally emerges.

3.4. Decoherence-Based MWI

Mainly following David Wallace´s influential *The Emergent Multiverse* [39], in this subsection, -after having discussed all major rival interpretations above, I take the unmodified framework of QM to be the one thing that has defied any criticism that has so far been launched. This is hence the interpretation that regards the framework as both empirically adequate *and* complete. Interpreting the formalism realistically essentially means *taking it seriously;* as such, interpreting the unitary evolution of the wavefunction realistically without any modifications or adding further ingredients unavoidably leads to the Everett Interpretation or MWI, the inception of which can be traced back to physicist Hugh Everett in the 1950s.

Let us finally inspect more closely what 'taking the formula seriously' implies; it suggests a 'collapse' to one definite outcome, or that a 'state reduction', in fact, never takes place or only *appears* to do so. In MWI, as opposed to CI, there is neither a causally effective observer, nor is there an abrupt quantum-to-classical transition, or Heisenberg-cut; this is such that quantum mechanics might, in an ad hoc manner, be assumed to stop working at the classical level. It is, quite to the contrary and in accordance with the general aim of unifying physics, assumed that, given that everything consists of a QM structure, a macroscopic structure likewise is subordinated to its laws. Hence, without adding additional hidden mechanisms, the unitary universal wavefunction [6] in its entirety, including its initial set of eigenstates, cannot possibly cease to exist. The only reason why they, except for the measured outcome, *appear* to vanish is the mechanism of decoherence [48]. Here is why, in a nutshell:

Since any measurement apparatus (and indeed the environment it presupposes) involves an enormous number of interacting particles, the effective wavefunction to be measured not only consists of the (prepared) particle itself, but also of the enormity of particles that constitute the apparatus and environment (a minor disclaimer: here I am using the term *particle* out of custom and convenience. By now, it should be clear that this does not imply a point-like ontology, however, decoherence is what will ultimately constitute a reasonably well-localized wave packet in a certain measurement setup). Due to an unavoidable spread of ordinary local physical interactions, which is a natural consequence of the measurement process, or indeed, the measurement process *itself*, the whole participating particle conglomerate becomes entangled eventually. Due to its complexity, one particular state to be measured, such as the particle position of x_1, will then be hopelessly out of phase relative to another position x_2: then, from the relative 'point of view' of x_1 (plus the environmental states it is entangled with), other position states (plus their respective entangled environment) *effectively disappear* due to non-interference (for the record, while interference becomes negligibly small, it does not disappear totally. This is also why branching is regarded as a continuous process, and as a consequence, *branch counting* is best understood in a coarse-grained sense).

These alternative (however similarly real and 'unaltered') position eigenstate-outcomes (qua state vector components), in turn, are entangled with yet another set of environmental particle state components. Each entangled 'state conglomerate monstrosity' will then eventually constitute a 'branch' or world, whereas non-interaction between *these* is practically guaranteed due to the effective impossibility of interference.

Wallace elaborates the following:

> "*Notice that it is not merely the linearity of quantum mechanics which allows us to interpret superpositions as instantiating multiple structures. Rather, it is the disappearance of interference terms between the relevant terms in those superpositions*." [39], (p. 68)

Following Wallace, describing this state of affairs in a formal toy model may look like the following:

$$(\alpha\psi_{x1} + \beta\psi_{x2}) \otimes \varphi_0 \rightarrow \alpha\psi_{x1} \otimes \varphi_{x1} + \beta\psi_{x2} \otimes \varphi_{x2}. \quad (15)$$

Here, the pre-measurement state can be taken as superposition of particle position eigenstates x1 and x2, which in turn is coupled with a (still) superposed environmental initial state φ_0 (strictly speaking, such position eigenstates are non-normalizable delta-functions, hence unphysical. However, when putting limited resolutions of detectors into account, one ought to regard them as a mixture of position eigenstates, i.e., a 'gaussian spikes'). As decoherences process in time, each conjunct on the right-hand side of the equation then expresses individually entangled states consisting of effectively two environmental states, φ_{x1} and φ_{x2}; one is entangled with measurement outcome $\alpha\psi_{x1}$, while not interfering with $\beta\psi_{x2}$, and vice versa. For both particle position states ψ_{x1} and ψ_{x2} then exist as an entangled set, whereas each can be taken as a world; however, both are relatively out of phase to the other, thus they no longer interfere.

Following Carroll and Singh [47], a slightly more detailed representation of this state of affairs in bracket notation might be the following: this treats the to-be-measured quantum object, apparatus *and* environment as quasi separate wavefunctions, which, however, become entangled during the measurement process:

$$|\psi> = (\alpha\ |+>_q + \beta\ |->_q) \otimes |0>_a \otimes |0>_e \quad (16)$$

$$(\alpha|+>_q|+>_a + \beta|->_q|->_a) \otimes |0>_e \quad (17)$$

$$\alpha|+>_q|+>_a|+>_e + \beta|->_q|->_a|->_e. \quad (18)$$

In this formal representation of decoherence, the index 'q' stands for the quantum to-be-measured object, 'a' represents the apparatus and 'e' the environment. Therefore, when, for instance, the spin-pointer states of the quantum object, represented by $|+>$ and $|->$, each become entangled with the wavefunction of the apparatus 'a' being in the $|0>$−state (16), then both spin states $|+>$ and $|->$ evolve into a tensor product representing 'q' & 'a' -*coupling*; - 'a' then effectively differentiates itself (borrowing this notion from

Wallace [39]) likewise into a $|+>$ and $|->$ state while the environment still remains in $|0>-$state (17). However, given that entanglement spreads to the environment, it too becomes part of the newly formed wavefunction products for both ($\pm$) states. This final time step (18) then effectively accounts for a world branching taking place. Ultimately, both factorized product states will be hopelessly out of phase; however, without any asymmetry of 'realness', both have to be regarded as equally existent.

What is important to notice here is that, at any rate, it is the relative complexity of such highly entangled many-particle states that causes the practically zero interaction between branches:

> "*So, in the case of chaos, 'worlds'—that is, emergent quasi-classical systems—are constantly splitting from one another. And since the system's state is always a mixture of reasonably localized wave-packets, the failure of classicality which we predicted for isolated chaotic systems will not occur here.*" ([39], p. 84)

While orthodox MWI still has to add distinct worlds 'by hand', so to speak, I take it to be an advantage of dbMWI that no such ad hoc addition has to be made; the bare formalism, plus rather complex tensor products and dynamics, which reasonably follow on from complex matter arrangements within our universe, are all that is needed to let branches emerge.

4. Discussion

As argued throughout this review, a realist interpretation of the bare formalism and structure seems to be what is left 'alive' after carefully inspecting all major interpretations and rival theories; and this alone suffices to let worlds emerge. Hence, while it was shown above that rival interpretations and theories face severe conceptual problems or collapse into a structure isomorphic to MWI, MWI itself seemingly straightforwardly follows, without adding any ad hoc ingredient and when only applying the bare formalism to arbitrarily complex quantum systems, -and the latter are something to be expected when applying it to our messy world. The sheer fact that this alone (bare formulism and decoherence) saves empirical adequacy and appearances is an achievement that cannot be overemphasized. Above that, the '*reductio* strategy' of this paper only leaves MWI 'alive' for its benefits that it neither faces the circularity issues that anti-realist interpretations do, nor the problem that it can only be applied to a restricted domain of quantum physics.

However, this should and will not mask the fact that the perplexing metaphysical consequences it yields are far too much for many to bear, or, in fact, are willing to tolerate. More often than not, it simply ignites an "incredulous stare". Such a reaction is, of course, merely emotional.

It is noteworthy however that even among Everettians there is no absolute agreement in terms of ontology and metaphysical consequences, for instance, when it comes to the aforementioned egalitarian view in terms of realness of individual eigenstates: here, Lev Vaidman [49] argues that $|\alpha^2|$ and $|\beta^2|$ measure *unequal* 'degrees of existence', if $\alpha \neq \beta$. While being an interesting concept, I fear however that 'degrees of existence' is conceptually vague and potentially problematic. Here, an adaption of Lewisian 'indexicality of actuality' [50] might be a promising alternative. Then, 'degrees of existence' might not be absolute but an indexical or relational value depending on the location within the multiverse (however, discussing this goes beyond the scope of this review. At any rate, even if 'degrees of existence' is true, a MWI still follows, as the better part of the state vector, at least in terms of reasonable approximations, is ontologically on a par. Hence, then also, a constrained version of branches, one with somewhat vague 'boundaries', seemingly follows.)

Also, according to the prevailing consensus at least, MWI also faces technical challenges, in particular, the problem of preferred basis or the meaning of probability in this context [51]. However, it might be fair to say that when embracing dbMWI in particular, a straightforward solution to the former seems to be at hand, as decohered quasi-classical states *are* what provide a preferred basis in a non-ad hoc manner, as discussed by Wallace [39] (here it might also be noteworthy that the preferred basis problem does not arise in the original Everett–Wheeler formulation, but does so as an artifact of the 'many worlds' language first published by de Witt and Graham in '*The Many-Worlds Interpretation of Quantum Mechanics*' [6] – though by following Everett´s unpublished notes).

There, Wallace also provides a fully worked out decision-theoretic analysis of probability. It is, however, also fair do admit that decision theory has been criticized as a basis of (QM) probability, but other solutions have been given, for instance, by Sudbury in 'The logic of the future in quantum theory' [52]. Sudbury´s alternative proposal is to understand probabilities in terms of non-classical truth values that are assigned to each potential outcome relative to a particular observer. However, this would turn truth into a relative notion and cannot account for the fact that from a 'view from nowhere' perspective, everything occurs with certainty: indeed, a view-from-nowhere account in terms of truth might be preferable. However, I agree with Sudbury when he states that decision theory may be irrelevant to passive agents and hence cannot possibly fully represent (QM) probabilities in their utmost general applicability. But a more general critique of a decision-theoretic account can be given. Similar to how Wallace himself criticized the lack of objective truthmakers in anti-realist interpretations, one might object that a decision-theoretic account of probabilities likewise requires an objective modal structure by which it is packed. Wallace talks of *branch weights* presumably doing that kind of work [39], but I would rather suggest the use of *local* relative frequencies, similar to Simon Saunders' recent proposal of an '*equi-amplitude rule*' in terms of branch-counting [53]; while *global* frequencies are indeed ill-defined within an 'Emergent Multiverse' in which allegedly *all* states are realized, *local* frequencies might hold relatively to respective decohered branches. For instance, if $|\alpha^2| < |\beta^2|$ holds for equation (17) within a particular branch, then relatively fewer sub-branches will exhibit $|+>_q$ than $|->_q$. In other words, relative frequencies in terms of ratios can be given: "*There may be no true number of the relevant microstates, in each case, but there may yet be true ratios*." [53] (as Saunders argues, instead of Vaidmanian 'degrees of existence', this may rather be an instance of [relative!] *numbers* of existence.). While Wallace argues in [39] that decoherence provides no well-defined notion of branch count, *I* would argue that it provides a *reasonably* well-defined branch count, in the same way it provides *reasonably* well-localized wave packets.

At any rate, the following might be something to be agreed upon and be sufficient for the overall argument of this review: whether ultimately to be captured in decision-theoretic terms, observer-relative non-classical truth values or relative frequencies, probability seems to be related to self-locating uncertainty either way; whether such probabilistic datum is to be ultimately understood as subjective in its nature or not, it does not seem ultimately to be crucial to the integrity of MWI. Thus, contrary to the conceptual issues of its rivals discussed in the main sections of this review, I would suggest that these problems ought to be regarded as second-order challenges, rather than arguments for immediately dismissing MWI as a viable interpretation.

Finally, I dare to make the following claim: poll results notwithstanding, the majority of the physics community in fact prefer (an unmodified) realist interpretation and are only Copenhagen advocates out of custom and convenience, or because they do not deeply question anti-realist assumptions or hidden-variable theories´ (limited) applicability. I dare to say that the majority may already *subconsciously* be 'many-worlders', and did not, mostly due to shut-up-and-calculate advice, rigorously reflect on their *consciously* preferred presuppositions or think them through to their logical endpoint. That is to say, even an advocate of the 'no-interpretation interpretation' may, when taking the formulae as something *substantial*, come to the same conclusion or at least utilizes MWI as a working hypothesis.

Another final argument in MWI´s favor may be that quantum information theory is much more easily reconcilable with MWI and both seem to converge, as argued above, towards one unified interpretation when putting forward OSR as a framework and taking the other conclusions drawn in Section 3.1 into account. In addition, decoherence-research is already heavily used in quantum computing, if only for the reason that *coherence* is what is trying to be technically achieved. Again, it, when being interpreted realistically, quite naturally leads to MWI branches without additional ingredients.

It might also be worth mentioning that both MWI and information-theoretic interpretations are, according to Wallace [17] (p. 9), by now, the two most popular ones among *physicists*. Ironically, attempts to recover interpretations that bring back a classical world-view are, for the most part, coming from philosophers. So much the worse for philosophy.

5. Conclusions

In this paper, the plausibility of two main claims have been argued:

Firstly, that rival interpretations or theories either face limited applicability/conceptual incoherence, or can be reduced to MWI on closer inspection. It has been discussed that there are four options for the anti-realist in general (and QBist in particular) in order to bypass conceptual incoherence: PEMWI, OSR–MWI, MWI and hidden variables. However, the first three views may themselves deflate under the assumption of OSR. Likewise, in Section 3.2, I hope to have demonstrated that under the presupposition of preserved consistency, the distinction between RQM and MWI eventually evaporates.

Secondly, up to this point, hidden-variables theories have seemed to be a viable alternative; however, while in the case of hidden-variables theory the threat may not be as grave as conceptual incoherence, compatibility with QFT might still dictate a modification that ultimately also leads, as argued, to an ontology that strongly suggests 'MWI implications'. Thirdly, *dbMWI* in particular may be regarded as the most straightforward interpretation of QM.

Thus, when adding all these provisional results together, MWI might indeed remain the only viable option. Even if some of the arguments propounded are not regarded as utterly sound, I still hope that the overall framework of this conceptual analysis may inspire others and be utilized for similar but improved future approaches. Finally, even if there is no agreement in terms of the overall conclusions drawn, it may nevertheless be sufficient to demonstrate that MWI is, if nothing else, *ripe* for being included in the consensus.

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