Realism Despite Underdetermination

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Summary

Recent arguments for the physicality of pure quantum states revive ontic interpretations of the wave function. The resulting proposals describe radically different worlds and make divergent predictions but not experimentally accessible ones as the technology stands—in effective terms, the interpretations are empirically equivalent, ruining the prospects of realist interpretation. One response, Partial Realism (PR), limits commitment to theoretical convergences at intermediate theoretical descriptive levels. PR looks for shared theoretical claims among the competing programs, In the quantum mechanical case, it looks for shared theoretical claims among the competing programs about, e.g., the psi state, micro-spatial structures, and the Bohr model. However, critics (notably Callender 2020) object that the common contents identified are meager. The objections include that the quantum state is the same only approximately; the shared micro-spatial structures hailed by realists are not quantum results and thus cannot help PR; the same goes for theoretical parts such as the orbits derived from Bohr's model, which rest on semiclassical theories; also raised are qualms about Bohmian realist accounts of reflection/transmission coefficients in the tunneling effect. Results such as these lead Callender to dismiss the PR strategy. This paper challenges his arguments and defends the strategy.

1. Introduction

The history of science abounds in theories that seemed right on target yet proved badly empirically underdetermined or radically wrong. Partial realists agree but add that, crucially, theories rich in corroborated novel predictions virtually always contain theoretical descriptions and models that gain retention in subsequent theories.

"Partial realism" (PR, aka "selective realism") is a blanket term for projects started in the 1980s that seek to separate the "wheat from the chaff" in such theories[1]. Partial realists focus on successful theories marred by false or dubious content or empirical underdetermination. They respond to the challenge by reducing the postulated theoretical content without eliminating it (as

[1] Seminal works include John Worrall (1989), Philip Kitcher (1993), Stathis Psillos (1999), among others.

radical empiricism strives to do). These realists admit that theories taken as monolithic constructs are typically false, and epistemic success is generally partial, especially at the most fundamental levels of description. Their goal is to confine realist interpretation to theory components that have achieved scientific corroboration and are free from specific doubts; the selected components tend to be comparatively abstract, coarse grained, and domain restricted (see, e.g., Saatsi 2005, Cordero 2011, Vickers 2013, Alai 2017, Egg 2017, and Cordero 2022).

ROAD MAP: The rest of this paper runs as follows. Section 2 outlines how recent argumentation for a physical interpretation of the quantum state revives interest in genres of ontic theories developed to address the quantum measurement problem. Yet, the ontology of the quantum world remains clouded by empirical underdetermination. Section 3 discusses an ongoing strategy to identify theoretical content shared by the leading ontic theories, and then lock the interpretation problem into a "theoretical bubble," leaving the rest of the world "safe from the underdetermination blight" (Partial Realism). Section 4 presents critical challenges to the relevance of the convergences identified by partial realists, most compellingly by Craig Callender (2020). Section 5 outlines how scientific realism has evolved over the last half-century from overly ambitious projects to a family of epistemologically cautious PR positions close to scientific practice. Section 6 examines the complaints against the PR strategy presented in section 4 and shows that they miss or misrepresent crucial aspects of the situation. The last section (7) concludes that the PR strategy does succeed in identifying limited but significant core of theoretical contents shared by the leading ontic models of quantum mechanics (QM).

2. The Case of QM

Quantum mechanics is an astonishingly successful family of theories tainted by conceptual problems, particularly the "measurement problem," that lead to realist solutions limited by empirical underdetermination. Answers to the found problems range from extreme instrumentalism (e.g., "Quantum Bayesianism," Q-bism) to strong arguments for ontic realism. On the instrumentalist camp, Q-bism rejects the idea that the quantum state of a system provides an objective description of it. To Q-bists, an agent's actions and experiences are the central concerns of quantum theory, and they view the state as a tool for assigning a subjective probability to the agent's future experience. To Christopher Fuchs, for example, the wave function describes the observer, not the world (2014).

On the opposite camp, realists advance arguments for an ontic interpretation of the quantum state, notably two. One is a theorem by Matthew Pusey, Jonathan Barrett, and Terry Rudolph (2011), showing that pure quantum states must correspond directly to physical states rather than "epistemic states," so we must regard them as "ontic" as opposed to representing incomplete states of knowledge about the physical world. A complementary realist reasoning focuses on evidence for the physicality of pure quantum states, a line represented by Harvey Brown's (2019) argument for taking the quantum state as an objective part of the physical world. He points to information strongly suggesting that the quantum state contains enough physical information to claim that the wave function of an individual system represents some real aspect of the system in question. The information is "physical" in that it describes how the system acts and reacts with the surrounding physical world. Among the quantum state-based evidence Brown invokes are details regarding the energy structure of quantum systems, energy exchange channels between their parts and with other systems, quantum amplitudes and probabilities, interference between material systems, entanglement, and quantum nonlocality, quantum limits to the principle of energy conservation, intrinsic quantum spin and spin-based interactions; the stability of matter, its scope and limits; the effective dynamics of quantum-probabilities (at different levels of description). In more concrete situations—he notes—the quantum state consistently accounts for numerous properties of material systems—e.g., the color of things, the probabilistic structure of superconductivity, electrons in molecular bonds (wavefunction shapes and their effects, e.g., in graphene and diamond); it even grounds the notion of "world."

There is an old fly in this realist ointment, however. While the noted lines strengthen the case for ontic psi, efforts to unveil the ontology of the quantum world remain marred by empirical underdetermination. The three most developed programs of ontic interpretation are Everettian quantum mechanics, Bohmian mechanics, and spontaneous collapse. These approaches describe physical worlds with different laws of nature and edifices, diverging markedly at various ontological levels. Bohmian mechanics postulates an ontology of particle(s) whose motion follows a guidance equation hooked up to the quantum mechanical wave equation. Many Worlds Everettians present macroscopic superposition as indicators of effective ontological multiplicity in physical reality. Collapse theorists modify the standard linear dynamical evolution of the wavefunction, changing the wave equation to produce a unified story of the macro and micro realms. The three programs are empirically distinguishable in principle but not experimentally (as technology stands). No practical crucial test between the theories seems likely in the foreseeable future (Q-computing might change things). None of the competing theories satisfies the methodological condition of successful novel prediction.

A caveat is in order before proceeding. The noted programs are empirically equivalent only in the non-relativistic domain (OQM: ordinary quantum mechanics), which is of limited interest. Still, the case is relevant to the realist project because the mentioned models of ordinary quantum mechanics theories illustrate how a "quarantine strategy" might help the realist by unveiling theory parts that are empirically successful, free of specific doubts, and deserve realist interpretation.

With the above qualification in mind, let us suppose we have three "effectively empirically equivalent" OQM programs, each describing a very different world in detail. We can't say one program is well-confirmed and approximately true if we know that there are two equally well-confirmed others that contradict its hypotheses. Effective underdetermination blocks theory choice. Some realists try to revert this judgment by turning up the "scientific" dial, using traditional epistemic features such as simplicity, unification, explanatoriness, and so on to decide which research program is best (Callender 2020). However, no agreement exists on how to carry out this option.

Alternatively, realists can focus on theoretical content shared by all the competitors and look for substantive theoretical claims found in all the competitors, regardless of their level of fundamentality. In this spirit, some thinkers dig for convergences at intermediate theoretical levels and use them as the core for a Partial Realism stance (PR) towards ontic QM (Cordero 2017, 2022). The expected gains are twofold: (a) Identification of theory parts on which the three sides agree, where the contents are free of underdetermination as far as the competing programs are concerned. (b) Make it explicit that the disagreements between competing camps are confined to just certain parts of the programs.

3. Partial Quantum Realism

One application of partial realism developed to handle the case exploits descriptive convergences at intermediate theoretical levels, a strategy advocated in Cordero (2001). Craig Callender (2020) terms it “Quarantining the Blight” because it seeks to lock the quantum interpretation problem into a theoretical Bubble“ and leave the rest of the world “safe from the quantum blight” (p. 82). The question is: Do the ontic programs considered share theory parts of legitimate realist significance? Or is commitment in OQM limited to the observable level? Let us agree with Callender that, to be interesting, the claims the PR strategy protects should be (a) theoretical, (b) not merely mathematical, and (c) specifically quantum mechanical.

As antirealists remark, the competing theories radically disagree at fundamental levels—e.g., there are no continuous Bohmian particle trajectories in collapse theories or Everett; collapse theories (unlike the other competitors) are indeterministic, and so on. The competing programs offer global descriptions that vary radically at the deepest level. On the other hand, there are promising convergences at intermediate (nonfundamental) levels of description—e.g., descriptions that allow for neutral identification of entities and processes over physical regimes of interest. Partial realists emphasize the availability of claims shared by the ontic competitors. In doing so they refer to non-fundamental entities, properties, and processes (see, e.g., Egg (2021)’s “effective ontology” regarding properties like mass and spin; also Cordero’s 2022 regarding state reduction as an abstract functional/effective process present in all the leading ontic competitors). Let us clarify with some examples.

(i) On the quantum state (psi): the three ontic competitors (collapse, MW Everettian, Bohmian) associate psi with an admittedly weird physical field. Psi is functionally the same entity in the three approaches (in collapse theories, post-collapse normalization changes the state slightly). All the competitors include the Schrödinger equation centrally in the dynamics; all endorse a strong form of ontic-structural non-separability, agree on the development of decoherence, also on atomic vibrations, as well as on geometrical relations between subsystems (internal quantum-molecular shapes, atomic and quark structure, etc.). As a result, the energy levels and the quantum average values for energy, distance, and many other magnitudes are effectively close in the models. So, although the full dynamics is structurally different in the collapse, Bohm and Many Worlds theories, all display considerable agreement at theoretical levels directly involving the wavefunction. This singles out the presence of approximate partial models shared by the three programs.

(ii) Other key commonalities related to psi point to numerous shared features, notably functional/effective descriptions, the spatial structure of molecules, and quantum entanglement. Consider the following examples.

> (a) The Many Worlds program is weird in that each quantum possibility is realized in some branch of the total state, and in that sense, all possibilities materialize in the physical world it describes. However, at the state-branches (worlds) level, the world that realizes a given possibility undergoes an effective quantum mechanical projection that reduces the local state accordingly.
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> (b) All the ontic theories agree on numerous "geometrical relations between subsystems (molecular shapes, atomic and quark structure, etc.)." For instance, all have the water molecule with the oxygen atom bonded to two atoms of hydrogen, the latter making an angle of about 104* with the former in "normal" thermodynamic conditions. We can thus take a realist stance about these theoretical descriptions and many others shared by the competing approaches.
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> (c) To mention one more key feature, the ontic theories all incorporate quantum entanglement.

However, Callender (2020) compellingly warns against the realist relevance of these and other suggested convergences. In his view, nothing can protect scientific realism from the underdetermination problems of OQM. He thus calls for popping the "quarantine bubble" offered by partial realists.

4. Pop the Bubble!

Callender (2020) denies the existence of relevant convergences between the highlighted theories. He admits that the three programs may agree on some theoretical features for some systems as we move into the classical limit, but he thinks such results are meager at best. For example, he thinks that while quantum decoherence occurs in all the competitors, leading to the effective suppression of quantum interference, this has virtually no realist significance. Decoherence may provide a defensible quarantine strategy that frees some insubstantial claims about unobservables, but he expects realists to do better than secure realism only in the classical domain of quantum theories (p.80). The issue, he stresses, is whether the proposed convergence-based partial realism can reach into the coherent quantum realm. He does not think it can. Here are some of his leading complaints:

4.1. On the psi field: The claim about the quantum psi state might ring true, he says, but at best, it is only *approximately true.*

> (a) The normalization in collapse events will change the state used. Differences in decoherence might imply slightly different Bohmian effective wavefunctions from the wavefunctions associated with branches in Everett.
>
> (b) Furthermore—the objection goes—the supposed agreement may only exist at the mathematical level. What psi stands for, what the quantum state represents, can be dramatically different between the three programs.
>
> (c) The most radical differences occur in the theories that add a non-linear stochastic component to the Schrödinger equation.

4.2. On molecular spatial structure: Callender points out correctly that the supposedly "safe" realist statements suggested about bonds and angles in Cordero (2001) are not genuinely quantum, so they don't support realism about OQM. Indeed, the currently used angle of 104.5 degrees does not come from OQM but from a crystallography experiment plus some minimal non-quantum theory (that would have been enough to figure the angle).

4.3. Callender underlines that orbits derived from Bohr's model are also not based upon OQM but upon semi-classical theories. He agrees that the claims in question are non-mathematical and about the unobservable level, but they are not quantum results.

4.4. On tunnelling (a purely quantum effect). Callender calls attention to the particle trajectories implied by Bohm's model, noting that because the probability density is positive, the velocity of the particles is determined to be positive (go forward). The particles that allegedly "reflect" from a barrier or discontinuity all have positive velocity, he notes. If so, the particles keep going forward, and nothing is reflected. Although the reflection coefficient is nonzero, there is *no reflection*, and the transmission coefficient is not one. There is thus a disconnection between the motion discernible from Bohm's theory and the standard realist interpretation of the reflection/transmission coefficients.

Based on the above and similar results, Callender claims that no theoretical membrane can protect scientific realism from the found underdetermination in a way genuinely beneficial to realism—the programs disagree too much down below. His recommendation is straightforward: "Pop the realist bubble"—reject Cordero's realist zone (comprising spatial structure, trajectories, etc.). Some models and systems may be safe, he concedes. But these would be more like "small, disconnected islands of reprieve," not anything like a quarantine zone realists can invoke to argue their case.

So, is the search for realist-relevant agreements at intermediate theoretical levels destined to fail? I'll argue that Callender's tempting objections misrepresent the realist claims. It will be good to start the discussion with some clarifications.

5. A Brief Detour on Scientific Realism

For much of the last century, leading "scientific realists" entertained very ambitious hopes regarding what makes a theory worthy of a realist interpretation ("RI"), such as the following:

R1. RI applies to whole theories (as opposed to bits of them).

R2. Theories deserving of RI apply universally, without restrictions.

R3. RI demands exact (as opposed to merely approximate) theoretical descriptions.

R4. RI fails if a theory T's central terms fail to refer.

R5. The theoretical descriptions licensed by T should be correct for the most part.

R6. A theory worthy of RI should make the intended domains intelligible in terms of the kinds of entities and processes that lie at the bottom of the ontology (fundamental description).

The above requirements articulate a conception of scientific realism that has been the subject of powerful critiques since the 1960s. These critiques, such as those by Thomas Kuhn on R4, Bas van Fraassen on R2, and Larry Laudan on R1, R3, R4, R5, are rooted in a historical context. R7, for instance, expresses a Cartesian ideal that Newton had already challenged in the 17th century. These and other negative appraisals have fueled arguments, particularly from the empirical underdetermination of theories by data, and skeptical readings of the history of theories.

Laudan's influential argument, for example, is based on the observation that past successful theories have generally turned out to be false at the deepest descriptive levels, leading to the conclusion that we have no reason to believe that currently successful theories are approximately true, let alone that there is a realist link between success and truth (1981).

In response, most scientific realists have relaxed their adherence to (R1 - R6), taking positions that are more modest and closer to scientific practice while reaffirming the realist link between novel empirical success and truth, now in terms of truth content rather than total truth. Partial realists, in particular, do not focus on theories as integral wholes, but instead concentrate on theoretical parts selected based on their local confirmatory grade (contra R1). They do not expect theories to hold universally (contra R2), allowing for approximate theoretical descriptions (weakening R3) and accepting theoretical content purged of problematic terms, regardless of their position in the original construct (contra R4). They also look for theories with truth content limited to restricted domains, as opposed to only theories that are true "for the most part" (contra R5). Partial realists accept non-fundamental descriptions as purveyors of welcome understanding and candidates for epistemic commitment (contra R6).

The resulting realist projects are comparatively modest. In them, lacking knowledge of the world at the most fundamental level is not incompatible with gaining knowledge of what the world is like at levels of lesser fundamentality. The "partial realist" strategy is explicitly non-fundamentalist: select only assertions confirmed beyond reasonable doubt, regardless of their level of abstraction, coarse-graining, and domain restriction.

From this perspective, well-confirmed scientific theories are probably approximately true, meaning that some novel theoretical accounts they give of the intended domain are true. I.e., many of the entities and structures they postulate exist independently of the scientists' minds and are as the theories say.

With these clarifications in mind, let us now consider Callender's objections to the PR approach.

6. A Realist Reaction

The complaints against the quarantine strategy outlined in Section 4 are tempting, but they miss crucial aspects of the situation and are unwarranted. Here are some realist replies:

6.1. Callender rejects the quarantine strategy for the ontic interpretations discussed in Section 3. One complaint is that saying that the field is the same in all the programs is, at best, "only approximately true." He expects assertions of shared content to rest on error-free (as opposed to approximate) theoretical descriptions. Selective realists drop this expectation as virtually unrealizable (the chance of ever having the one exactly correct theory on any field will be overwhelmingly low at any given time). Regarding the traditional requirements in the previous section, natural philosophers effectively abandoned R3 early in modern times, articulating explanatory representations that explicitly allow for approximate truth content instead. One instance is the kinetic theory of matter, which aimed to causally account for approximately rough empirical laws gathered over the previous centuries about the macroscopic behavior of gasses (e.g., $PV = NRT$) and materials (e.g., thermal expansion).

The question is: Do the three ontic theories share content relevant to the realist project? Not so by the overambitious (R1 – R7) standards, but yes by a sensible generalization of those standards. Much of the shared theoretical content holds over select theory parts rather than the whole theory (contra R1) and does so fruitfully if only approximately (contra R2 and R3). The content shared may occur outside the "fundamental levels" of the competing programs. (contra R4). Also, the content in question may hold correct over just some significant regimes rather than "for the most part" across the theory (contra R5), and the shared content may make the intended domains intelligible through descriptions of intermediate rather than fundamental theoretical level (contra R6). Admittedly, this suggestion runs against a philosophical expectation still entrenched in some quarters: 'Ontological descriptions must unveil the nature of entities and processes down to the deepest fundamental level.' Most of the basic sciences have abandoned this expectation, however. Following suit, partial realists settle for descriptions within explicit regimes of abstraction, generalization, and restriction of the domain under consideration.

So, here are replies to the objections to the PR approach reported in section 4.

1 (On psi): All the ontic competitors associate the quantum state with a physical field, all include the Schrödinger equation centrally in the dynamics, all endorse a strong version of ontic-structural non-separability, and all agree on geometrical relations between subsystems (internal molecular shapes, atomic and quark structure, etc.), among other convergences. While the

competing models diverge in some details about the exact psi-field, disagreements occur only over limited domains. Importantly:

(a) In the three ontic theories, the quantum state of a system structures the system's ability to produce effects over a spatiotemporal region. (Brown 2019). Psi's local intensity gauges the system's ability to exert and receive causal influence (interact) at spatial locations.

(b) As previously noted, the quantum state of a system provides specific physical information about it, like its energy structure, energy exchange channels between its parts and other systems, quantum amplitudes and probabilities, interference between material systems, entanglement, and quantum nonlocality, quantum limits to the principle of energy conservation, intrinsic quantum spin and spin-based interactions; the stability of matter, its scope and limits; the effective dynamics of quantum-probabilities (at all descriptive levels).

(c) Psi consistently accounts for many physical traits in more concrete situations. Examples include the color of things, the structure and effective properties of the "vacuum," the probabilistic structure of superconductivity, and electrons in molecular bonds (wavefunction shapes and their effects, e.g., in graphene and diamond); the state even grounds the notion of "world." Concrete applications of the part of quantum mechanics that centers on psi are legion. Consider, for example, spectral "fingerprints" of atoms, molecules, and material systems; cryptographic uses of quantum states; experimental quantum cloning; superposition instability and radiation (how an electron in an unstable state acts like a radiating antenna until it falls to a lower E-level); effective violations of energy conservation in the microworld; the role of retinal molecules in the detection of different light frequencies; and so on.

6.2. (On the realist import of spatial microarchitecture). Callender correctly states that many plausibly "safe" statements about bonds and angles are "not truly quantum," thus failing to provide confirmational support for quantum mechanical models. However, while this objection applies to the angle of the water molecule invoked in Cordero (2001) on behalf of quantum realism, it doesn't apply to properly *quantum mechanical* derivations-predictions of properties of water and ice (including its angle and many features of its spatial and dynamical structure). Take, for instance, the classical simulations of simple water models that reproduce many properties of liquid water and ice but overestimate the heat capacity by about 65% at ordinary temperatures (classical simulations do worse for low-temperature ice). One primary reason is that the *atomic vibrations are irreducibly quantum mechanical*. Harmonic quantum corrections to the noted molecular motion result in more accurate heat capacities for liquid water and ice at low temperatures (Qaiser Waheed & Olle Edholm 2011). Callender's (2020) rejection of the realist relevance of molecular spatial models overlooks the wider empirical success of quantum chemistry.

6.3. (On quantum tunneling): The complaints summarized in Section 4 correctly underline the "surreality" of Bohmian particles. The latter are bizarre, and there is no pretending otherwise. But this result is not damaging to the Quarantine Strategy because partial realists do not question that the competing projects disagree about whether the world is made of particles and the quantum field or just the latter, whether it is governed ultimately by stochastic or deterministic laws, whether there are one or many "effectively classical" worlds, whether there are particles in addition to psi, among other points of disagreement. These divergence areas are outside the abstract zone the PR strategy identifies as free of underdetermination. Particle talk does not fall in the quarantine zone. So, the noted convergences about the quantum state justify the suggested partial realist approach. There is also this matter of detail: The strange result about the absence of reflection found in the Bohmian analysis of tunneling is mediated by the specific modeling invoked. On that modeling, if the particle is in the region $x < 0$, it will move to the right toward the barrier—so it cannot possibly reflect. However, the modeling used is controversial. Further analyses of quantum tunneling in Bohm's theory yield different results. For example, Travis Norsen (2023) shows that the highlighted lack of reflection is an artifact of using unphysical (unnormalizable) plane-wave states. Norsen argues that real particles should be described as finite-length wave *packets* rather than unphysical plane waves.

7. Concluding Suggestions

So, does PR help the quantum realist? Here is how Ernan McMullin (1984) characterized the experiential ground zero of scientific realism at the beginning of the current debate:

> "The near-invincible belief of scientists is that we come to discover more and more of the entities of which the world is composed through the constructs around which scientific theory is built."

McMullin reacted to growing claims that science yields no substantive retention of theoretical description and no referential stability in theory change, powered by the antirealist critique of (R1) to (R7) listed in Section 5. McMullin's conception of epistemic success eschews that greedy version of realism. The critique of the quarantine strategy outlined in Section 4 is still attached to some of that version.

As previously mentioned, in the 1980s, the debates raised by antirealist arguments encouraged the development of realist projects, whose subsequent critique has led in the last two decades to selective realist proposals in which theoretical entities and regularities are identified by *what they do rather than by what they "ultimately are" or are made of.* Selectivist approaches look for theory parts that have been scientifically confirmed beyond reasonable doubt. A preferred way of pursuing this task is by subjecting the received theory parts to abstraction, coarse-graining, and domain restriction (e.g., Cordero 2011 and 2022; Vickers 2013; Alai 2021).

The responses on behalf of the quarantine strategy presented in Section 6 follow the working-level functional approach just highlighted. The shared content abstracted from the three competitors leaves open numerous questions—e.g., whether the quantum world is deterministic or indeterministic, among many others. Still, if the common core highlighted is legitimate, realists can and should invoke it to quarantine the diverging parts of the ontic quantum narratives. The epistemic yield envisaged differs from what some realists hope for, but the already unveiled content is arguably impressive. As McMullin hoped, "we come to discover more and more of the entities of which the world is composed through the constructs around which scientific theory is built."

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