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Scientific realism and underdetermination in quantum theory

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Abstract

This paper surveys the status of scientific realism in relation to quantum physics, focusing on the problem of underdetermination.

1 | INTRODUCTION

Scientific realism can be briefly characterised as 'a positive epistemic attitude toward the content of our best theories and models, recommending belief in both observable and unobservable aspects of the world described by the sciences' (Chakravartty, 2017). In addition to this *epistemic* attitude, scientific realism standardly involves a *metaphysical* commitment to 'the mind-independent existence of the world investigated by the sciences', and a *semantic* commitment to 'a literal interpretation of scientific claims about the world' (*ibid.*). Quantum theory has impacted the realism debate along each of these three dimensions. Here we will focus on its relevance for one of the most widely discussed arguments against realism's *epistemic* commitment: the underdetermination of theory by evidence. While there are other important arguments that have shaped the debate, here we aim to show that quantum physics presents us with a particularly striking instance of the problem of underdetermination, which can be thus regarded as one of the main challenges to realism about quantum theories.[1]

Defending realism towards a given scientific theory requires that one articulates their epistemic commitments: the cognitive content of their realist stance. This is most typically portrayed in terms of theory-based knowledge about the unobservable. In a nutshell, defending a realist attitude towards quantum theory is hard, because it is difficult to say what in the quantum realm one can justifiably be a realist *about*. The challenge is *not* one of inherent incompatibility of realism and quantum reality. The problem is not that quantum theory is bound to be incompatible with the kind

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of objectivity and mind-independence that the metaphysical and semantic dimensions of realism require, for example. Rather, the problem is that there are *too many* quantum theories, each underwriting different realist commitments.[2] Given the degree to which these competing theories are compatible with the empirical evidence, it is difficult to justify any one of them as unambiguously supporting specific realist commitments towards unobservable aspects of quantum reality. This is the gist of the underdetermination problem. We will discuss different facets of this problem in connection with non-relativistic Quantum Mechanics (QM) in Section 3, and then in relation to Quantum Field Theory (QFT) in Section 4. In Section 5 we go on to survey different realist responses to these challenges. But first of all we will briefly review some key aspects of QM as it is described in physics textbooks.

2 | TEXTBOOK QM AND THE MEASUREMENT PROBLEM

Applied to QM, scientific realism calls for an articulation of scientific knowledge about physical systems like atoms or semiconductors (to name just two famous examples), which cannot be successfully described by classical physics, but require a quantum theoretical description. The first problem the realist faces is in pinning down the theory that should inform these knowledge claims.

There is, of course, a fairly standard 'textbook' presentation of QM that students typically first get taught. Among other things, this involves associating the state of a physical system (a collection of particles, for example) with a mathematical object called the *wavefunction*, the temporal evolution of which is described by *Schrödinger's equation*. Empirical content is then extracted from this mathematical apparatus by means of the *Born rule*, which allows one to calculate probabilities for obtaining certain measurement results, given the wavefunction and a choice of the property to be measured (the so-called *observable*).[3]

Textbook QM is well-known to give rise to the *measurement problem*. It relates to the fact that the states of quantum systems can form *superpositions*: linear combinations of wavefunctions which themselves correspond to possible states of the system. In the simplest case, one considers an observable the measurement of which can only yield two possible results (the standard example is electron spin along a given axis, with two possible measurement outcomes 'up' or 'down'). The general state of a system with respect to such an observable is a superposition of the two states corresponding to the two possible measurement outcomes. The linearity of the temporal evolution of the system and the measuring instrument (as well as their broader environment), as given by Schrödinger's equation, implies that upon a measurement a superposition state (e.g., of an electron) evolves into a superposition of the states corresponding to the two measurement outcomes (e.g., measured 'up' and measured 'down'). However, we never seem to observe such superpositions.

The measurement problem can be formulated as an inconsistency. Tim Maudlin (1995, 7) identifies the following three claims as mutually inconsistent:

> [1] The wave-function of a system is *complete*, that is the wave-function specifies (directly or indirectly) all of the physical properties of a system.
>
> [2] The wave-function always evolves in accord with a linear dynamical equation (e.g. the Schrödinger equation).
>
> [3] Measurements of, for example, the spin of an electron always (or at least usually) have determinate outcomes, that is, at the end of the measurement the measuring device is either in a state which indicates spin up (and not down) or spin down (and not up).

QM textbooks standardly evade this problem by introducing a postulate to the effect that whenever a measurement is performed, the wavefunction 'collapses' into the state corresponding to the obtained measurement outcome. This amounts to abandoning claim 2, because the collapse of the wavefunction is a nonlinear process in conflict with Schrödinger's equation. The problem with this is that it rests on an *ad hoc* distinction between situations in which nature follows Schrödinger's equation and situations in which it does not. The only 'principle' guiding this distinction is the requirement that measurements must have determinate outcomes. The notion of 'measurement' is painfully vague and unprincipled, but imposing this requirement nevertheless suffices for making impressive predictions about a great variety of experimental outcomes for various quantum systems.

'Textbook' QM works well in practice, but due to the measurement problem it is far from clear how it should inform the realist's epistemic commitments. Arguably it is better regarded (as far as realism is concerned) as a *recipe* for predicting experimental outcomes, as opposed to a physical theory describing unobservable reality (Maudlin, 2019), and for the latter many realists are inclined to look beyond physicists' standard predictive recipe.

Before turning to the different ways of doing that, let us note a general point about the status of the wavefunction. The ad hocness of the collapse postulate may be viewed as unproblematic if the wavefunction is not taken to represent an element of physical reality. One could, for example, adopt an instrumentalist stance according to which the wave-function is just a part of a mathematical machinery useful for deriving empirical predictions. Such instrumentalism would of course give up on scientific realism, along with its typical credo that central theoretical terms refer (e.g., Psillos, 1999). (The wavefunction arguably is a central theoretical term of QM.) A less radical view is that the wavefunction refers not to the physical state of the quantum system, but to an agent's knowledge about it. Such an *epistemic* (as opposed to *ontic*) reading of the wavefunction has come under attack by powerful recent theoretical results, such as the Pusey-Barrett-Rudolph (PBR) theorem (Pusey et al., 2012), but these results do not rule out all non-ontic interpretations of the wavefunction (Ben-Menahem, 2017). A very modest form of realism can appeal to such an interpretation (see Section 5.6), but most realist approaches to QM subscribe to an ontic reading of the wavefunction. This still leaves wide open what the wavefunction represents, as we will next see.

3 | UNDERDETERMINATION AND QM

Studies in the foundations of quantum theory have led to different physical theories according to which the wavefunction unambiguously *represents* aspects of mind-independent reality that lie behind (and can explain) observable quantum phenomena. Three broad strategies can be identified. One is to drop the collapse postulate and to supplement textbooks' other principles with a novel interpretation pertaining to the Born rule and the probabilities it involves. By taking at face value the superposition aspect of quantum states (represented by the wavefunction), this path leads to Everettian Many Worlds theory. In terms of the above formulation of the measurement problem, this approach amounts to abandoning claim 3, because it holds that all possible measurement outcomes actually occur (albeit in 'different worlds'). Another strategy is to abandon claim 1 and to add further theoretical structure ('hidden variables') to supplement the wavefunction. This leads to pilot-wave theories (such as Bohmian mechanics). Finally, one can abandon claim 2 in a principled, non-ad-hoc way by changing the Schrödinger dynamics so as to give up on its deterministic and linear character. This approach is taken by dynamical collapse theories (such as the Ghirardi-Rimini-Weber theory, GRW).[4]

What is significant for the scientific realism debate is that (i) all these paths lead to prominent variants of QM that have theoretical content capable of informing the realist's epistemic commitments; (ii) all of them are compatible with the currently available empirical data (subject to certain qualifications to be discussed in Section 5.3); (iii) they can offer radically different worldviews in terms of what exists at the quantum level and how it dynamically evolves over time. In the light of this theoretical state of the art, the challenge faced by the realist is already plain. If the realist goes by the empirical data alone, she is equally justified in opting for any one of these theories to inform her realism. Which theory is she going to choose and why? It looks like her theory-choice is bound to be informed by theoretical, extra-empirical considerations. The challenge is then to clearly articulate and justify these considerations on grounds that are compatible with the realist's epistemological outlook at large.

We'll consider a range of possible realist responses in Section 5, but for now let's look at a further aspect of this challenge. Even if the problem of underdetermination as set out above could be solved, there would still be multiple metaphysical options compatible with each variant. Recall the disagreement concerning the status of the wavefunction introduced above. Even if it is accepted that the wavefunction requires an ontic reading, this does not suffice for realism, for it leaves the metaphysics of the wavefunction entirely underdetermined. Theorems that rule out particular statistical and epistemic interpretations of the wavefunction do contribute to scientific knowledge, of course, by showing what the world *cannot* be like. This kind of theoretical knowledge goes some way towards satisfying the realist's epistemic ambitions. But in and of itself it pays lip service to the realist's claim to defend scientific knowledge about quantum aspects of the world pertaining to electrons, atoms, etc. For what kind of knowledge can one claim to have if all we know of electrons, say, is captured in the mathematical representation of their quantum state, but we do not even know *what kind of thing* a 'quantum state' is?

Again, the problem is not that there is no way to make sense of the notion of quantum state. The problem is that there are *too many* ways to make sense of it. The contrast between the metaphysical alternatives is stark. In some interpretations the wavefunction partakes in reality by virtue of being part of its *nomological* make-up, that is, part of the laws obeyed by the 'stuff' material objects are made of.[5] This stuff (also referred to as 'local beables' or 'primitive ontology') can in turn be conceptualised in different ways, for example as particles in Bohmian mechanics or 'flash' events associated with the wavefunction collapses in GRW. This nomological interpretation of the wavefunction stands in contrast with theories that construe it akin to a real field occupying a space. What kind of field and which space? Again, there are radically different metaphysical options. Since the wavefunction (in the simple case of a system of N particles without spin) is defined on a 3N-dimensional configuration space, a straightforward metaphysical interpretation takes it to be a field in this space. By contrast, our experiences of a 3-dimensional world motivate attempts to interpret the wavefunction as an object (called a 'multi-field') in 3-dimensional space. Yet other interpretations view the wavefunction as representing properties of physical systems.[6]

At this level of description the challenge is to spell out what one can claim to know about reality by virtue of knowing which wavefunction to associate with a given physical system. This challenge can be further sharpened by looking at different contexts in which quantum theory is put to a concrete explanatory use. Realists tend to pride themselves on their ability to explain (along with scientists) natural phenomena by reference to the reality behind the observations, and justification of scientific theories is allegedly partly a matter of 'inference to the best explanation'. But how does quantum theory actually explain even the simplest phenomena involving quantum interference, tunnelling, or the spin-magnet interaction? In so far as the activity of explaining plausibly requires correctly representing the reality behind such phenomena, one must arguably turn to one or another variant of QM capable of underwriting realist commitments. It turns out that the ensuing explanations are highly dependent on the theoretical path one chooses to follow, even for the simplest and most paradigmatic quantum phenomena, such as quantum tunnelling or the Stern-Gerlach experiment (Callender, 2020; Saatsi, 2020). The issue of how the virtues of alternative explanations can be rationally compared remains murky by the lights of the epistemic standards that scientific realists adhere to in general.

Finally, it is worth highlighting the fact that these challenges are firmly anchored in widespread expert disagreement, unlike the underdetermination worries that have traditionally exercised realists after Duhem and Quine. These latter worries stem from the general idea that any set of empirical data taken to confirm a given scientific theory could equally well be taken to confirm a different theory, as long as the two theories are empirically equivalent, that is, they make the same empirical predictions. This general kind of underdetermination is no longer viewed as a serious threat to realism:

> Most philosophers of science. . . concede that it is always *possible* that there are empirical equivalents to even our best scientific theories concerning any domain of nature, but insist that we should not be willing to suspend belief in any *particular* theory until some convincing alternative to it can actually be produced: as Philip Kitcher puts it, "give us a rival explanation, and we'll consider whether it is sufficiently serious to threaten our confidence". (Stanford, 2017, Section 3.2)

As we have seen, QM actually confronts us with such serious rivals (see also Dieks, 2017).

4 | UNDERDETERMINATION AND QFT

QFTs are quantum equivalents of classical field theories, and thus deal with systems of infinitely many degrees of freedom. Similarly to non-relativistic QM, relativistic QFT, as it is presented in most textbooks, is a highly successful predictive recipe, but not the kind of physical theory that could straightforwardly inform realism about the physical world. In a sense, the situation here is even worse, because the very formalism of QFT suffers from serious mathematical difficulties. In particular, in QFT some of the terms that need to be calculated in the course of deriving empirical predictions are divergent. The need to deal with these infinities has given rise to several different research programs. For our purposes, these can be classified into two groups: First, there are the so-called conventional (or Lagrangian) approaches, which make use of various renormalization techniques in order to tame the badly behaved mathematics of the formalism (Wallace, 2006). Second, there are various attempts to put QFT on a sound axiomatic basis, the most important one being the algebraic approach (Halvorson, 2007; Ruetsche, 2011).

Doreen Fraser (2009, 2011) has characterized this as a genuine case of underdetermination, but that characterization is itself controversial, because it is not really the case that the two approaches yield the same empirical predictions. If anything, it is a *potential* case of underdetermination, premised on the expectation that the algebraic approach will someday be empirically viable. At present there is no realistic model in 3 + 1 space-time dimensions that satisfies the axioms of algebraic QFT. Insofar as scientific realism is motivated by the empirical success of science, there is thus a clear incentive to focus one's attention on conventional QFT, because it is within this framework that most of the successful applications of QFT to high-energy physics, most notably the standard model of particle physics, are derived (Wallace, 2006, 2011). On the other hand, scientific realists (like philosophers in general) should care for conceptual rigour and clarity, and some have argued that this should direct their interests towards algebraic QFT (Fraser, 2009, 2011; Kuhlmann, 2010).[7]

This debate is connected to several other issues of importance for scientific realism.[8] One question concerns the kind of entities that QFT is fundamentally about. Some results from axiomatic QFT cast doubt on interpreting QFT in terms of particles or, more generally, quanta (Fraser, 2009; Halvorson & Clifton, 2002; Malament, 1996; Ruetsche, 2011). The obvious alternative, then, would seem to be an interpretation in terms of fields, but this turns out to be equally problematic, in part for the same reasons as the particle interpretation is (Baker, 2009; Bigaj, 2018). Particles and fields do not exhaust the space of possibilities for an ontology of QFT, but it is fair to say that no other proposal has so far gained widespread acceptance (Kuhlmann, 2020, Section 5.1).

The failure to settle on a unique fundamental ontology for QFT may be due to another point of disagreement between the different approaches: In what sense, exactly, is QFT supposed to be *fundamental* ? The central role of renormalization in the conventional approach highlights the fact that QFT is, according to this view, an *effective* theory, not a strictly fundamental one. (This opens an interesting route to a novel kind of realism about quantum physics, see Section 5.5.) By contrast, the axiomatic approach is at least compatible with viewing QFT as truly fundamental, but as we have just seen, this still does not uniquely answer the question what realism about QFT amounts to. In fact, Ruetsche (2011, 2015) argues that different instances of QFT's empirical success depend on different (mutually incompatible) ontological commitments, speaking against realism. Finally, let us not forget that the controversies discussed in the previous section do not simply disappear when we turn from QM to QFT. After all, QM is supposed to be the non-relativistic limit of QFT, so the stark differences between the different variants of QM must already be present in different variants of QFT (Barrett, 2014). Indeed, each of the proposals to modify the QM formalism mentioned in Section 3 suggests at least one research program for implementing its specific commitments within a relativistic framework (for Bohmian mechanics, see Dürr et al., 2014; Struyve, 2011, for GRW-type theories, see Bedingham, 2011). To the extent that these competing research programs are viable, the underdetermination problem from QM persists unabatedly in QFT (although see Section 5.3 for a possible rejoinder to this worry).

5 | REALIST RESPONSES TO QUANTUM THEORY

Realist epistemology has hitherto paid only limited attention to quantum theory, but a range of responses to the underdetermination problem has emerged over the recent years.

5.1 | Wait-and-see

Least satisfyingly, perhaps, one could in principle adopt a wait-and-see attitude. There is scope for empirically (dis-)confirming some alternative theories of QM (most notably of the GRW variety, see (Bassi et al., 2013)) in so far as these are not exactly empirically equivalent with the standard quantum recipe. More generally, one could regard the different theories as competing, potentially fruitful research programmes the fate of which will be (hopefully!) determined in the fullness of time. As a recent introduction to the philosophy of QM puts it: 'Given our epistemic situation, the best strategy is to keep all of the serious theoretical options on the table while we aim for something better' (Barrett, 2019, 231). Such a patient quietism is not very satisfying for a philosopher who aims to delineate the limits of our current scientific knowledge, however. If we cannot determine what kind of realist attitude is justifiable towards our current best and most successful physical theories, what life is left overall in the realist movement as a going concern? The recognition that radically different theories of QM can be predictively so immensely successful (in the non-relativistic domain) also threatens a basic motivation for realism encapsulated in the 'no-miracles' argument, according to which only realism can explain the empirical success of science (Chakravartty, 2017).

5.2 | Breaking the underdetermination 1: Metaphysics

A popular strategy amongst philosophers of physics is to draw on metaphysical considerations to adjudicate between alternative, equally empirically successful theories.[9] For instance, the virtues of a 'primitive ontology' of local beables have been welcomed in this spirit as offering a metaphysics that makes QM much more continuous with classical physics, and therefore (the thought goes) preferable for the realist. As Valia Allori (2015, p. 320) puts it, theories of QM incorporating local beables are capable of offering a realist 'a new but clear explanatory scheme, on the lines of the classical one, to account for the macroscopic world in terms of its microscopic constituents'. This explanatory scheme is claimed to be superior to approaches without a primitive ontology, such as Everettian QM or other views that take reality to consist of just the wavefunction, on the grounds that such approaches fail to adequately account for our experiences in physical (as opposed to configuration) space (Maudlin, 2010).

The continuity of Bohmian mechanics and the primitive-ontology accounts of GRW with classical physics can be questioned, however. For example, the Bohmian particles are radically non-classical by virtue of having no properties apart from their spatial location: mass, momentum, charge, or spin are best understood as features of the wave-function, their attribution to the particles being contextual and dependent on the experimental arrangement (Esfeld et al., 2017). Regarding GRW, the ontology of 'flashes' associated with the stochastic collapses of the wavefunction has no classical analogue, and the alternative GRW ontology of the 'mass density' field also radically revises the classical conception of point particles. Furthermore, even if one accepts the idea that the metaphysics of QM best contain some kind of local beable, one still faces an underdetermination between different variants of primitive ontology. While the realist can appeal to plausibility considerations to rule out some of these (Esfeld, 2014), it is doubtful whether this forces a choice for a single option. For these and a number of further reasons, the explanatory advantages of introducing local beables as ontological primitives have been contested (Albert, 2015, chapter 7; Egg, 2017).

In general, metaphysical grounds for breaking the underdetermination can be difficult to justify as part of a defensible realist epistemology. Everyone agrees that quantum metaphysics is bound to be radically non-classical and unintuitive in one way or another. We can try to adjudicate between the alternative theories by using the methods of contemporary metaphysics, but are these methods reliable enough to justify a scientific realist attitude toward any particular theory as ‘approximately true’? Saatsi (2019, 2020) argues that well-known anti-realist arguments challenge thus framed realist commitments, due to the unavoidable involvement of ‘deep’ metaphysics that transcends the limits of reliable scientific reasoning.

5.3 | Breaking the underdetermination 2: Physics

Alternatively, the realist can try to break the underdetermination through extra-empirical considerations that are internal to physics. Staying closest to physics' practice, it has been argued that compatibility with special relativity is the sine qua non for an empirically acceptable quantum theory. Hence one might hope that the underdetermination problem described in Section 3 only concerns the nonrelativistic regime, whereas only one of the candidate theories encountered there will be capable of being extended to a relativistic QFTs described in Section 4.

More generally, one can argue that the apparent problem of underdetermination is a result of a skewed conception of ‘quantum theory’. For example, a conception of QM as ‘fundamental’ is strikingly pervasive amongst the advocates of both pure wavefunction realism and primitive ontology.[10] This is hard to square with the fact that the arguments for these positions and the debate between them is almost exclusively concerned with a non-relativistic (and therefore obviously non-fundamental) theory. Everyone concerned is surely aware of the non-fundamental status of QM, so in what sense is the ontology being discussed fundamental? Most plausibly, the ontology pertains to a fictional world in which QM is fundamental, the rationale for which is underwritten by an expected ontological similarity between QM and any future truly fundamental theory, such that ontological lessons about QM somehow carry over to the real world.

David Wallace (2020a, 2020b) has criticized this rationale, drawing attention to the profound conceptual differences between QM and QFT, the theory constituting the next step towards fundamentality: ‘most of the features of nonrelativistic quantum theory appealed to by metaphysicians of quantum mechanics are emergent approximations at best in QFT’ (2020b, 94). This poses particular problems for those approaches which (like Bohmian mechanics or GRW) depend on modifying the ‘textbook’ QM, because existing attempts to carry over these modifications from QM to QFT have not yet passed the stage of hopeful research programs. Accordingly, Wallace detects in the current metaphysics of QM a widespread failure to address the complete framework of quantum theory, as opposed to just a single theory within that framework (namely nonrelativistic QM). In his view, the Everett interpretation is the only satisfactory response to this situation, hence underdetermination disappears as soon as we look beyond nonrelativistic QM.

This argument can be resisted in several ways. First, one can question whether the Everett interpretation is even a candidate for a satisfactory view of the empirical world. In addition to the metaphysical considerations adduced in Section 5.2, this can be motivated by ongoing criticism of the Everettian attempts to account for the Born-rule probabilities (Dawid & Friederich, 2020; Dizadji-Bahmani, 2015). Furthermore, one might claim that other approaches addressing the complete quantum theoretical frame-work (e.g., Bub's information-theoretic view, see Section 5.6) are just as acceptable to the realist as the Everettian approach. Finally, one can argue that the alternative research programs mentioned at the end of Section 4 are advanced enough to count as genuine rivals to an Everettian account of QFT.

5.4 | Structural realism

One prominent realist response questions the premise that the various quantum theories really are radically different from one another in a relevant sense. Structural realism is the view that our best scientific theories correctly describe the structure (and nothing but the structure) of reality. The notion of ‘structure’ (vs. ‘nature’) is a natural one to appeal to in disentangling the underdetermined quantum metaphysics from what it is in quantum physics that a realist can trust. Roughly speaking, the thought is that while the different quantum theories are strikingly dissimilar in their metaphysics, they nevertheless share common and well-established structural features that one can rely on in spelling out realist commitments.

At the level of detail it is not clear what comes of this strategy, however. In so far as structural realists defend knowledge about the structure of the world, an account is needed of the worldly structures represented by the abstract mathematical structures shared by the different quantum theories. According to structural realism "the metaphysical import of successful scientific theories consists in their giving correct descriptions of the structure of the world," as James Ladyman (2014, Section 2) puts it. But even if the structural realist can point to certain structures (of entanglement or symmetry groups, for example) which all the different versions of QM have in common, these competitors give radically different replies to the question of how those structures are implemented in the physical world (Esfeld, 2013). Hence 'it is not at all clear that [the competing theories of QM] have in common any structure *of interest for realism*' (Ruetsche, 2018, p. 300).

More generally, the connection between quantum physics and structural realism turns out to be less intimate than it may initially appear. For one thing, the prominence of structural realism in contemporary realist epistemology does not specifically rely on quantum theories. John Worrall (1989) famously appealed to classical physics to motivate structural realism by reference to the transition from Fresnel's ether theory of light to Maxwell's theory of the electromagnetic field, and the so-called 'upward path' to epistemic structural realism is based on some general empiricist principles instead of any particular scientific theories (see Frigg and Votsis (2011, Section 3.1)).

Quantum physics has more directly motivated 'ontic' structural realism (OSR), but the latter is somewhat disconnected from the epistemological issues in the realism debate. There are historical connections, since Ladyman (1998) introduced OSR at least partly as an improvement on Worrall's earlier epistemic version of structural realism. However, these historical roots in the debate on scientific realism have little systematic significance in contemporary discussions of OSR, as is clearly indicated, for example, by two recent reviews of OSR in connection with modern physics (Lam, 2017; McKenzie, 2017). Another seeming connection between the realism debate and OSR consists in the fact that one well-known argument for OSR does appeal to underdetermination in quantum theory, involving the possibility of viewing quantum particles as individuals vs. non-individuals (see, e.g., French, 2019, Section 6). Interestingly, in this case the underdetermination has not been taken to support agnosticism or epistemic humility with regard to the empirically underdetermined aspect of reality. Rather, the advocates of OSR have drawn from it a metaphysical conclusion, to the effect that there are no objects at the fundamental level. All this suggests that OSR is better understood as a position in the debate on the metaphysics of nature than as a position regarding the nature and extent of scientific knowledge. It has been argued that the blatantly metaphysical commitments of OSR are in tension with the considerable level of epistemic humility associated with epistemological structural realism (Saatsi, 2010).[11]

5.5 | Effective ontology

Another way of finding common structure in seemingly disjoint versions of QM starts by noting the non-fundamental character of QM (mentioned in Section 5.3), which extends to QFT as well (at least in the conventional approach, see Section 4). The recognition that our present QFTs are effective field theories has led to a novel response to one of the most pressing questions confronting contemporary realism, namely how to select from a given successful theory those parts which deserve realist commitment (Fraser, 2018, 2020; Williams, 2019). Most relevantly for our purpose, this involves rejecting what Porter Williams (2019, 233) calls a 'quixotic focus on fundamental structure.' This new kind of selective realism instead draws attention to the ontology inherent in effective theories. While the latter do not pretend to inform us about the fundamental nature of things, they still arguably tell about what is real, or what exists. One may wonder how this can be, given that effective theories are neither fundamental, nor contain information about their relation to the more fundamental theories. A possible response is that the ontology of an effective theory is given by specifying the functional role of its theoretical posits, which only depends on their place *within* the effective theory and not on their relation to a fundamental ontology. The notion of effective theory generalizes beyond QFT (Rivat, 2021), and it is potentially beneficial to selective realism more broadly.

To see the relevance of this meta-ontological perspective for underdetermination, recall that the problem could be at least partly solved if a substantial overlap among the different theoretical variants could be identified, such that the realist could be committed to it, while remaining agnostic about the theoretical disagreements. Quite some time ago, Alberto Cordero (2001) argued that this is indeed the case in QM. He even gave some concrete examples of defensible realist commitments in the face of the looming threat of underdetermination, such as the structure of the water molecule as it is described in QM. However, Craig Callender (2020) has accused these examples of either not being genuinely quantum physical or being subject to underdetermination after all. He argues that the knowledge about the structure of water molecules, for example, actually results from experiments and theoretical considerations independent from QM. Conversely, *distinctly* quantum phenomena such as tunnelling and two-path interference are, according to Callender (2020, 68–70), explained in radically different ways by different versions of QM. In a similar vein, Juha Saatsi (2020) examines the case of spin and questions the possibility of substantial realism about it due to a radical underdetermination regarding what 'spin' means in different variants of QM. In the ensuing debate this negative verdict has been contested by Matthias Egg (2021), who argues in response to Saatsi and Callender that 'textbook' QM has an effective (or functional) ontology that should be regarded as common ground between the different variants of QM, despite their deep disagreements about fundamental ontology. According to Egg underdetermination thus does not threaten realism about spin or (at least some of) the examples discussed by Cordero and Callender.

5.6 | Minimizing representational content

Carl Hoefer (2020) proposes that we best give up on realism altogether in relation to fundamental physics, including quantum theory, while maintaining a realist attitude towards non-fundamental physics, as well as chemistry, micro-biology, and so on. This proposal faces the challenge of drawing a (sufficiently) principled distinction between 'fundamental physics' and the rest. This is a non-trivial matter, since arguably all the motivations for realism about the latter (including the ones that Hoefer specifically invokes in relation to non-fundamental sciences) apply equally to significant parts of quantum physics (Saatsi, 2020).

Indeed, the fact that quantum physics is one of the most successful areas of science by all measures (predictive, unificatory, instrumental) motivates scientific realism as forcefully as anything in modern science: if there is anything we *should want* to be realists about, it is quantum physics. But perhaps realism underwritten by the stunning empirical success of physics need not amount to a commitment to theories' (approximate) truth or to scientific knowledge about quantum reality. Saatsi's (2020) 'progress realism' renounces such commitments, while arguing that we are nevertheless justified in believing that quantum theories' empirical success is due to their robust representational relationships to reality. According to Saatsi (2020) the realist is justified in committing to the existence of a detailed, realism-corroborating metaphysical account of this empirical success, as well as to quantum physics' continued theoretical progress, while admitting that such an account lies outside our grasp (at least for now).

Other philosophers have argued that we should give up even on this most minimal commitment to quantum theories as theoretical *representations* of how the world is in its quantum respects. According to Richard Healey's (2020) 'pragmatist quantum realism', quantum theory 'teaches us about the world not by offering models by which to represent it, but by advising us on how it may meaningfully be represented, and how likely is each meaningful representation to be true' (144). More concretely, physical properties of a system are represented by magnitude claims (e.g., about energy, or components of position, momentum, or spin), which are not directly given by the quantum formalism. What that formalism provides (by means of the Born rule) is 'good advice to any user of quantum theory about the significance and credibility of magnitude claims about physical systems' (130). Whether this account of the explanatory power of QM satisfies the scientific realist's standards is a matter of dispute (Wallace, 2020b, Section 5.2).

The same is true for information-theoretic approaches to QM and for the approach known as 'QBism'. Versions of the former have been defended by James Ladyman and Don Ross (2013) and Jeffrey Bub (2016), but they have been accused by Egg (2019) of not being sufficiently realistic. Christopher Fuchs (2017) advocates the latter as a kind of 'participatory realism', but many scientific realists will not only insist that QM has more representational content than QBism allows, but will also balk at the lack of mind-independence that this view attributes to the reality described by QM. Moreover, since participatory realism is itself a further metaphysical option alongside the ones we have already encountered in the previous discussion (and a fairly radical one, as acknowledged by Fuchs himself), it aggravates rather than solves the underdetermination problem.

6 | CONCLUSION

QM presents a serious problem of underdetermination of theory by evidence. The problem can be traced to the measurement problem, but it acquires additional complexity from debates about the ontology of QM, the status of the wavefunction, and the alternative approaches to QFT. Traditional ways of dealing with underdetermination, by appealing to metaphysical or scientific principles, have not been very successful in the light of these complexities. This motivates the search for novel ways of addressing the problem. This in turn requires substantive rethinking of what exactly scientific realism amounts to, highlighting the importance of the problem for the future development of the realist epistemology.

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ENDNOTES

[1] Another prominent set of arguments revolves around a historical challenge to realism. For a recent view on how quantum physics bears on this challenge, see Vickers (2020).

[2] This is not to say that the underdetermination problem is the only motivation for questioning realism about quantum physics. In fact, a certain hostility to scientific realism can be traced back to the origins of quantum theory (Becker, 2018; Beller, 2001), and notable later attacks on scientific realism based on quantum theory have relied on arguments other than underdetermination (e.g. Fine, 1996). In particular, Bell's theorem plays a crucial role for many of these arguments, but there is an ongoing controversy about its relevance for realism (Lewis, 2019; Myrvold et al., 2020).

[3] The formal details do not matter for our discussion. See Ismael (2020) for an introduction and a commented bibliography of QM textbooks and books on philosophy of QM.

[4] These different approaches are sometimes described as different 'interpretations' of a single theory ('QM'), but it is more appropriate to view them as predictively equivalent rival theories (Acuña, 2021).

[5] Such a nomological construal of the wavefunction can be furthermore coupled with either Humean or non-Humean metaphysics of laws.

[6] For a fuller survey of these and other forms of realism about the wavefunction, see Chen (2019). There is also the possibility to be a realist about the quantum state, but to view it as being represented by a density matrix instead of a wavefunction (Chen, 2020).

[7] One can also ask whether the different approaches to QFT should be regarded as rivals at all, or rather as 'complementary, yet partial pictures of QFT, pictures with significant overlap, differential advantages and no deep incompatibilities' (Swanson, 2017, 8).

[8] Some of these connections are rather intricate and likely to generate confusion. See Egg et al. (2017) for an attempt to disentangle them.

[9] In the realism literature this approach has in general terms been defended by Musgrave (1992), for example.

[10] For example, within the 10 essays collected in Ney and Albert (2013), the word 'fundamental' (or 'fundamentally') appears more than 360 times.

[11] See Benitez (2019) for a recent attempt to bring OSR closer to the epistemological concerns of the realism debate, which is also sensitive to the framework character of QM mentioned in Section 5.3.

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