What Ontology for Relational Quantum Mechanics?[1]

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Abstract

In this paper, we evaluate some proposals that can be advanced to clarify the ontological consequences of Relational Quantum Mechanics. We first focus on priority monism and ontic structural realism and argue that these views are not suitable for providing an ontological interpretation of the theory. Then, we discuss an alternative interpretation that we regard as more promising, based on so-called 'metaphysical coherentism', which we also connect to the idea of an event-based, or 'flash', ontology.

Introduction

In the last 25 years or so (Rovelli 1996), relational quantum mechanics (RQM henceforth) has attracted the attention of many philosophers working in the field of quantum mechanics (Laudisa 2001 and 2019, Brown 2009, Dieks 2009, van Fraassen 2010, Candiotto 2017, Calosi and Mariani 2020, Dorato 2016 and 2020, Ruyant 2018, Pienaar 2019, Martin-Dussaud, Rovelli and Zalamea 2019, Di Biagio and Rovelli 2020, Vidotto forthcoming).

In the assumption that RMQ is a plausible interpretation of quantum theory[2] theory, this paper aims to evaluate the main proposals that have been advanced to clarify the ontological consequences of RQM. In more detail, we shall first focus on priority monism (Ismael and Schaffer 2016) and ontic structural realism (Candiotto 2017) and argue that these views are not suitable for providing an ontological interpretation of RQM. In the second half of the paper, we

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[2] Here we are not evaluating RMQ.

discuss an alternative that we regard as more promising and put forward a view according to which the ontology suggested by RQM is one of mutually interdependent physical systems.

The structure of the paper is as follows. In the first section we briefly present the essential tenets of RQM. In the second section we evaluate the monistic reading of RQM, while in the third we evaluate Candiotto's relation-centered analysis. After having critically assessed these two interpretations, we bring to bear a recent proposal by Calosi and Morganti (2021) and Morganti (2019) and argue that quantum systems as described by RQM are best understood in terms of mutual dependence as per 'metaphysical coherentism'. Before closing, we briefly consider the role that Rovelli himself attributes to events in the context of RQM. We suggest that both an ontology of events (or 'flashes') and coherentism represent viable answers to the question: *what is RQM about*? In fact, we will argue, the two views are compatible with each other.[3]

1. A brief presentation of RQM

In this section we briefly present RQM. The content of the theory can be summarized via the following principle:

(P) Quantum systems only acquire definite values for their state-dependent properties through interactions with other information-gathering physical systems.

P claims that state-dependent quantum properties do not have absolute values that could be regarded as intrinsic features of the physical systems that possess them. They are instead essentially *relational* since they depend on interactions between their bearers and other physical systems. The outcomes of these interactions can be described as *events* of the form 'system S_2 acquires property C with respect to, and due to an interaction with, system S_1 at time t_1. Notice that P does *not* imply that the qualitative content of quantum systems is entirely extrinsic, nor that properties only exist insofar as interactions lead to the acquisition of determinate values. In this connection, two remarks are in order. As to the first, it is important to stress that RQM involves only a proper subset of the properties of quantum systems, namely the *state-dependent ones*. In fact, at least prima facie, state-

[3] For an interpretation of quantum mechanics in terms of events, see (Dorato 2015).

independent properties cannot possibly be regarded as relational as required by P, since to be relational is defined here as 'depending on the state of a distinct physical system'. Concerning the second remark, we believe that it is entirely possible for actually existing properties of physical systems not to correspond to fully manifest, determinate values. For instance, one might interpret the pre-interaction properties of quantum systems as dispositions (Dorato 2016), or as ontically indeterminate – e.g., as determinables without a corresponding determinate (Calosi and Mariani 2020). In both cases, such properties would be actual and physically real in spite of their not having determinate and detectable values. For now, however, let us focus on the key feature of RQM, namely the principle of relationality (P).

As an illustration, consider a quantum system *S* and two observers[4], *F* and *W*, in a Wigner's friend scenario. In Rovelli's approach, two different observers "can give different accounts of the same physical sequences of events" (Rovelli 1996, p. 4). Suppose that the quantum system *S* is in a superposition of spin states[5]

$$|\psi\rangle_S = a\,|\uparrow\rangle_S + b\,|\downarrow\rangle_S \qquad (1)$$

where, as usual,

$$|a|^2 + |b|^2 = 1 \qquad (2)$$

Let us now suppose that Wigner's friend *F* correlates with *S*. Due to the linearity of the evolution, at t_1 we have

$$\text{ready}\rangle_F\,(a\,|\uparrow\rangle_S + b\,|\downarrow\rangle_S) \rightarrow a|\,\text{up}_F\,|\uparrow\rangle_S + b|\,\text{down}_F\,|\downarrow\rangle_S \qquad (3)$$

Let us further suppose that upon measurement, at t_2 *F* measures spin up:

$$|\psi\rangle_S = a\,|\,\text{up}_F\,|\uparrow\rangle_S + b\,|\text{down}_F \downarrow \downarrow\rangle_S \rightarrow |\text{up}_F\,|\uparrow\rangle_S \qquad (4)$$

Relative to Wigner (*W*), who at t_2 has not interacted with the joint system *S+F* yet, the state is instead a superposition of the form

[4] It is important to recall that in RQM 'observer' refers to any quantum system whatsoever.
[5] We are indebted here to Federico Laudisa, who helped us formulate the following two paragraphs in a clearer way.

$$a|up_W|up_F\ |\uparrow>_S + b|down_W\ |down_F\ |\downarrow>_S \qquad (5)$$

In other words, according to the information available to him, Wigner can find with probability $|b|^2$ that his friend has observed, say, spin down (see 5). But, according to (4), this seems to contradict *F*'s observation that at t_2 S has already a determinate spin-up value (for a similar reconstruction, see Brown 2009, p. 693). Consistently with quantum mechanics, objectivity can be reestablished only when *F* and *W* correlate and relativize their descriptions to their different observations, which for clarity we refer to as (A) and (B).

(A) *According to Wigner*, *F* has measured either spin up or spin down (see 3), but upon *W's* further observation on the joint system at t_3, there is a non-zero probability that *W* finds $|down_F\ |\downarrow>_S$ (see 5).

(B) *According to F*, instead, at t_2 his own measurement resulted in spin up (see 4), hence the probability for spin down went down to 0.

However, when Wigner and his friend correlate, they agree on both (A) and (B), which crucially includes a relativization of measurement outcomes to observers: intersubjective agreement is regained.

The foregoing leads to a question concerning the identity of the events that correspond to the acquisition of determinate values by physical properties: given the relative/relational nature of qualitative profiles in RQM, how is one to make sense of the abovementioned expression "different descriptions of the *same sequences of events*"? We can assume that the identity of a sequence of events is either intrinsic or relational (dependent on relations with other events). How should we choose between these two alternatives? What does it mean, in RQM, to talk of *sameness* of events having different descriptions relative to different systems, as stated by Rovelli in the above quotation?

If it made sense to talk about "the *same* sequence" described in two different ways by, say, *F* and *W*, there should be an absolute state of the matter about the state-dependent properties of physical systems. For, if the qualitative profile of a physical systems is entirely *analysable* in terms of interaction events, and the latter have an objective, perspective-independent content, then it follows that the qualitative profile of physical systems is also an objective, perspective-independent matter, and this holds, in particular, for the state-dependent properties that RQM focuses on.[6] But this conflicts with (P). If *tertium non datur*, it follows that in RQM the identity of outcomes/events (supposedly, the building blocks of the physical content of spacetime) must be extrinsic, that is, relational/structural. This conclusion is reinforced by the following passage: "There is no physical meaning to the state of an isolated system. A physical system (or, more precisely, its contingent state) is reduced to the net of relations it entertains with the surrounding systems, and the physical structure of the world is identified as this net of relationships" (Laudisa and Rovelli 2019, p. 1).[7]

Thus, the relational nature of quantum properties in RQM entails that, strictly speaking, it makes no sense to talk about different descriptions of the *same* event or chain of events. If, to be more dramatic, we replace 'physical system' with 'observer',[8] every "physical observer" "experiences" certain events from a particular perspective (say, Wigner's), which always includes an essential reference to the perspective of some other observer (his friend *F*). There is nothing more to reality than this. However, notice, this does not entail solipsism. Indeed, solipsism is avoided exactly to the extent that there is no isolated system: any "perspective" can only actualize (though in different ways) in relation to other "perspectives" and, far from being a subjective image that replaces reality, each perspective is exactly what constitutes physical reality.

Coming now to the question concerning the ontology of RQM, in view of the foregoing two options seem to emerge:

1) A strongly monistic ontology, according to which the truly fundamental physical entity is the universe as a whole, which, however is constituted by a plurality of systems that acquire a physical characterization only in relation to one another;
2) A structuralist ontology, according to which relations between physical systems are more fundamental than the systems themselves and their monadic properties.

[6] This claim depends on the assumption that the term 'analysable' does not denote some perspective-dependent relation of determination. We acknowledge that this is debatable (thanks to Claudio Calosi for making us see this), but we will omit a discussion of this issue here, since it is not crucial for our present purposes.
[7] Notice that this rules out what might in fact look as a third option: namely, that physical systems actually possess objective, non-relational properties in the form of determinables without a corresponding determinate. While arguments in favour of this view can be provided (see Calosi and Mariani (2020)), Rovelli (2019) seem to endorse a sort of verificationist viewpoint and discard such properties as physically meaningless since they would be in principle epistemically inaccessible.
[8] Though not all physical systems are observers, we can assume that observers are particular physical systems.

Option 1) may appear quite natural given the characteristic features of RQM: if only the perspectives of the whole existed, there would be nothing with respect to which these perspectives *would be perspectives of*.

Option 2) is also prima facie plausible, and in recent work it has been explicitly presented as *the* correct ontology of RQM. Nonetheless, in the next two sections we will argue that neither of these views is suitable for providing a metaphysical interpretation of RQM.

2. Why RQM is incompatible with priority monism

In the literature on metaphysical fundamentality, and following Schaffer's paper (2010), one usually distinguishes between two kinds of metaphysical monism: 'Existence monism' and 'Priority monism'. While the existence monist claims that *there are no* parts *and only the whole exists* (Horgan and Potrč 2000, 2012), the priority monist grants the pluralist the existence of parts but at the same time "holds that the whole is prior to its parts, and thus views the cosmos as fundamental, with metaphysical explanation dangling downward from the One" (Schaffer 2010, p. 31).

In the present context, the notions of fundamentality and priority are usefully linked to explanation: *what is metaphysically (more) fundamental corresponds to what plays the role of (more) basic explanans in our best scientifically-grounded account of reality*. Translated in physical language, we could say that the whole, or the One, is the universe *U*, including its non-observable parts. Its "explanatorily dependent" parts involve, say, the seeds of galaxies resulting from cosmic inflation, or the planets in the Solar system. Consider, in particular, the cosmic background radiation revealed by the WMAP.[9] To the extent that it, together with other pieces of evidence, confirms the Big Bang theory of the universe, we can say that the initial state of the Universe *is* the whole that, together with the laws of cosmic evolution, acts as the fundamental explanans for every later physical event.[10]

The existence of an initial state of the Universe dating 13,77 billion year ago, however, might be taken as an objection to RQM. If this state were "pointlike" it could not be interpreted in relational terms. However, as soon as at that state there existed hypersurfaces of some kind, RQM would still be applicable because U *would have parts*. toFurthermore, so far we have no

[9] The acronym stands for 'Wilkinson Microwave Anisotropy Probe' and denotes the spacecraft that measured the differences in temperature between various parts of the universe, with the aim of testing cosmological models. A representation of the gathered data is given in Fig. 1.

[10] The dependence relations invoked by the monist, therefore, are both diachronic and synchronic.

evidence about the nature of the Big Bang, because plausibly at the initial singularity quantum effects would be present and so far no quantum theory of gravity has been confirmed

For the sake of the argument, however, let us suppose that at the Big Bang there was no system in terms of whose state we might relationally ascribe a property. On this hypothesis in fact, U would have no parts, nor would there be anything external to it). It would follow that RQM cannot explain in its framework the status of *at least one non-relational state, namely the initial state of the Universe*[11]

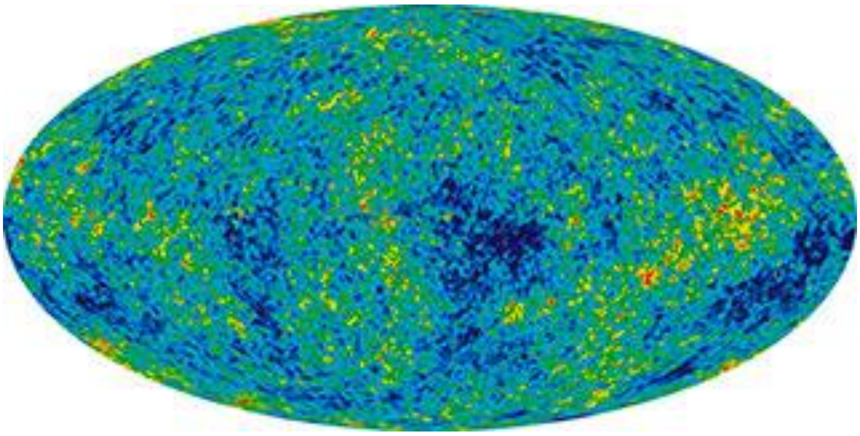

FIG. 1

This difficulty is another illustration of the fact that one's modus ponens is another's modus tollens. . Since priority monism appears instead to be perfectly applicable to the initial state of the universe, it would in any case follow that RQM and priority monism are incompatible. However, if only because of the working assumptions of the present paper, which presupposes the validity of RQM, we will argue here in favour of the opposite viewpoint. Namely, that RQM is perfectly compatible with the claim that the initial state of the universe has no determinate (state-dependent) properties, while priority monism is not.

Let us start with a quotation from Rovelli: "Do different observers *O* and [*P*] get the *same* answers out of a system *S* is a *meaningless* question. It is a question about the *absolute state* of *O and P*." (Rovelli 1997, p. 204). What RQM rules out is, then, the possibility that a physical system can be in a determinate state *independently* of some other physical system – that is, in an absolute, non relational, manner. However, it would be an additional, and to our mind unwarranted, claim to infer from this that RQM requires that at least two physical systems exist.

[11] We owe this important remark to one of the referees.

Indeed, the supporter of RQM can, and should, contend that the initial state of the universe is 'special' in the same way in which the total state of the universe is: in both cases, since there is no external 'observer', the physical system being considered does not have definite values for its state-dependent properties.great!

On the other hand, the same sort of considerations arguably renders priority monism unworkable in the present context. For, the universe has undeniably evolved from its initial state, coming to possess (parts and) determinate state-dependent properties. But if there is something with respect to which U acquires determinate properties, it cannot be external to U, since U is all there is. Hence, it must be identified with one or more of its proper parts P_i. This, however, contrary to the requirements of priority monism, entails that the universe U cannot be explanatorily prior to P_i since, for the determinateness of its properties, the former depends on the latter.[12]

What we are claiming, notice, is not that what is (meta)physically fundamental must have absolute values for *all* its properties: it is well-known that in quantum mechanics not all properties of a physical system can possess definite values.[13] The idea is, rather, that if U is more fundamental than its parts (as priority monism requires), then it cannot depend on them in any way, and it must instead be the case that the parts depend on U for their properties. However, according to RQM, neither is the case. On the one hand, U doesn't have definite properties independently of its parts. On the other hand, the properties of any proper part of U (even the smallest) must always be defined with respect to some other proper part of U, and never essentially depend on U as a whole.[14]

In anachronistic but evocative language, any of these parts of U can be compared to a Leibnizian monad, representing or "reflecting" U from its particular perspective. The separation between U and the monad reflecting it is ontologically basic. The main difference with Leibniz's monadology is, of course, that in relational quantum cosmology there is 'no monad

[12] One may object that U could be dependent on itself. However, besides violating the sensible requirement that nothing can be its own full ground, and in general explanation/ontological dependence should not be reflexive, this contradicts the basic postulate of RQM according to which the property-defining events consists of proper interactions, which take place among numerically distinct entities.
[13] We are obviously referring here to Kochen and Specker's theorem.
[14] Here, a pluralist about fundamentality could object that different relations may track different forms of ontological priority/dependence. Notice, however, that here it is dependence with respect to something's 'qualitative profile' that is at stake. And while it makes sense to think, say, that a whole is mereologically dependent on its parts but at the same time the parts are dependent on the whole for their properties, it is hard to see how the whole could be fundamental with respect to qualitative profile if a) it doesn't have determinate properties by itself and b) the parts may obtain their determinate properties via 'local' interactions with other parts. With respect to a), one may retort that fundamental properties need not be determinate: we will get back to this in a moment.

of the monads' since, as we have seen, each system can only have (as a matter of ontological, not merely epistemic, fact) partial information about *U*.

How could one attempt to reestablish the consistency between priority monism – which appears in any case plausible in view of quantum mechanical non-separability[15] – and RQM? First, it could be contended that in order to ground the determinate properties of the parts, the fundamental entity need not have determinate properties. Here, we cannot enter a detailed discussion of fundamentality and indeterminacy (for a recent discussion, see Mariani 2022). We just note that the burden of proof would in this case be on the monist, who should explain how determinateness can emerge (albeit in a local and perspectival manner) from what is fundamentally indeterminate. Especially so in view of the fact that, as pointed out earlier, Rovelli seems to explicitly think that it is physically meaningless to attribute to physical systems states that allegedly describe state-dependent properties independently of interaction.

Secondly, one could hold that priority monism only applies to classical, non-quantum universes, while RQM addresses quantum mechanics . On this hypothesis, it would not be possible to discuss the consistency of the two theories since they would apply to two *different* domains (classical and quantum respectively). However, this strategy would obviously not be successful. Apart from the fact that priority monism is quite often discussed in a quantum regime – entanglement being regarded as an important evidential support (Schaffer 2010) – here we are discussing whether priority monism is a good interpretative stance with respect to (RQM), that is relational *quantum mechanics.*

A third strategy to reconciliate priority monism with RQM consists in claiming that, as a matter of fact, RQM is compatible with the idea that there is an absolute state of the universe. In particular, one could contend that there in fact *is* a definite quantum state of the universe *before* any correlation between it and any of its parts and that, crucially, the information exchange caused by interaction has just the *epistemic function* of revealing it. To the extent that priority monism seems to call for definite relations between the whole and its part, the consistency with RQM would be vindicated: the whole would be prior to the parts, and the latter would be prior to it only in the "innocent" epistemic sense that reference to available information provided by them is necessary for us to uncover the objective, fundamental properties of the whole. The fact that the word "information", which is used a lot in the context of RQM, has an epistemic overtone may certainly add plausibility to this argument.

[15] See among others Ismael and Schaffer (2016).

This proposal, however, would be tantamount to abandoning RQM. First, the notion of "exchange of information" in RQM has, controversially but purportedly, a mind-independent meaning.[16] At most, one could argue that the interaction or exchange of information between a part *P* of the universe *U* and the remaining part *U-P disturbs* the prior definite state of *U*. However, it is a fundamental tenet of RQM (recall principle (P) above) that definite properties of physical states[17] do not pre-exist and are literally generated by physical interactions or correlations.

This point can be reinforced by considering the historical development of quantum theory. One could identify the early phase of the 'Copenhagen interpretation' championed by Bohr with the idea that measurements affect pre-existing, objective facts. But, as Jan Faye, for instance, has plausibly argued, in his response to EPR Bohr himself abandoned this view (Faye 1991). After 1935, Bohr explicitly defended instead the view that state-dependent quantum magnitudes are fully indeterminate before measurement since they are entangled with the measurement apparatus.

In a nutshell, an 'ignorance' or 'disturbance' interpretation of standard quantum mechanics is arguably empirically inadequate, and this was acknowledged even by Bohr's archenemy, John Bell: "the word ['measurement'] very strongly suggests the ascertaining of some pre-existing property […] Quantum experiments are not just like that, as we learnt especially from Bohr. The results have to be regarded as the joint product of "system" and "apparatus", the complete experimental set-up" (quoted in Whitaker 1989, p. 180). Given the close resemblance between Bohr's philosophy of quantum mechanics and RQM (Dorato 2020), it is plausible to conclude that this is also the case for RQM, which definitely seems to be intended by Rovelli as more than a merely epistemic interpretation of quantum theory.

Before closing this section, we should point out two additional reasons for believing that there is conflict between RQM and priority monism, namely (1) the former's *locality* vs the latter's holism (2) the former's symmetric nature vs the latter's asymmetric arrow of explanation.

Starting from (1), contentious as this may be, Rovelli argues that RQM is an entirely local theory. To see the grounds for this claim, let us go back to the familiar Wigner-type scenario already considered above. In RQM, the interaction between the system *S* and Wigner's friend *F* is always local, exactly as the interaction between *S+F* and *W*. More generally, according to

[16]On this point there is a huge literature. For a defense of the view that information has a physical meaning, see Adlam and Rovelli (2022).

[17] State dependent ones, as not above.

RQM, in any EPR-type setup involving two space-like entangled systems A and B the measurement outcome obtained locally in the? wing A of the experiment does not interact with the outcome obtained in the distant wing B (and conversely). Unlike what happens in Bohmian mechanics, in RQM there is no action at a distance. Therefore, from the viewpoint of Wigner, who is located in A, the outcome in B revealed by her far away friend *F* is indeterminate, even though, given the property of the singlet state, it is possible for him to *predict* with probability 1 that *F* will measure, measures, or has already measured[18] a perfectly correlated or anticorrelated outcome. Clearly, while compatible with monism, this stress on the locality of interaction of two quantum systems pushes towards a pluralistic ontology.

As for (2), according to priority monism metaphysical hypotheses invoking the whole as a common ground for all the 'local' matters of physical fact (Ismael and Schaffer 2020) presuppose the *asymmetric* character of the relation of explanation (hence, dependence/grounding). If a whole with its set of properties A (the universe) is *explanatorily prior* to the properties of its parts B, then the set of properties A *grounds* the set of properties B and it cannot the case that B explains or grounds A. *Consequently, it seems that priority monism implies the existence of a necessarily asymmetric relation of dependence/grounding*.

However, in the context of RQM explanation is essentially symmetric, in a sense of dependence that is not altogether different from the coherentist notion defended below in 4. In fact, in RQM, when A interacts locally with B, thereby acquiring some determinate (B-relative) properties, the same occurs to B in relation to A (regardless of whether or B is the universe as a whole). It might be objected that when a macroscopic instrument B measures some property of the quantum system A, the atomic system *A* acquires very little information from *B*, since it interacts only with a few of its atomic constituents. This, however, is a merely epistemic fact connected to the circumstance that the magnification of the properties of A is needed for pragmatic reasons related to prediction and testing. In any measurement scenario, the flow of information between A and B is still symmetric and two-way.[19] Pending further arguments to the effect that the symmetric dependence between physical systems is derivative on an asymmetric dependence of all physical systems on the cosmos, this again pushes towards a pluralistic ontology in which priority monism is fale.

[18] The disjunction is due to the relativity of simultaneity.

[19] In order to provide further arguments to defend the symmetric character of RQM's explanation we could adopt for a moment the language of dispositions: the manifestation of a certain disposition of A to reveal one of its eigenvalues triggers the manifestation of the disposition of B to reveal one of its eigenvalues *and conversely* (Dorato 2010 and 2016).

3. RQM and Ontic Structural Realism

Another option that has been explored recently is to interpret RQM in terms of an ontology of relations. In particular, Candiotto (2017) has argued that RQM is naturally understood as supporting a structural ontology as advocated by defenders of Ontic Structural Realism (see also Vidotto forthcoming).

Ontic Structural Realism (OSR) is the conjunction of an epistemological thesis and an ontological thesis. The *epistemological* thesis is that:

The discontinuity across theory-change in the history of science emphasised by scientific anti-realists is compatible with a degree of structural (formal) continuity, and the empirical success of science is best explained in terms of the (approximate) truth of the preserved structural claims (Structural scientific realism – SSR, for short)

The ontological thesis has it that:

Reality is at root relational, in the sense that physical relations are more fundamental than (or at least as fundamental as) objects (Ontic Structuralism – OS for short).[20]

OSR corresponds to SSR plus OS. It was originally endorsed based on the idea that turning structuralism from an epistemological to an ontological thesis 'fills the gap', so to put it, between epistemology and metaphysics. For present purposes, we can set the realist component aside and focus in particular on OS, i.e., the claim that reality as described by our best current science – especially physics – is fundamentally analysable in terms of relational structure.

This structuralist ontological component is, quite importantly, often endorsed on the basis of contemporary physics and its allegedly relational nature. Arguments that have been invoked in favour of OS include (but are not limited to) reference to the following: the underdetermination between individuals and non-individuals in quantum mechanics, the role of group-theory in quantum theory and the analysability of properties in terms of invariance, permutation symmetry in quantum statistics, weak identity conditions for space-time points as

[20] The option of relations being as fundamental as the objects they relate is mentioned only for completeness - in particular, to include so-called 'moderate structural realism' in our general presentation of the view. It is the more radical, eliminative form of OSR that is invoked by Candiotto.

a solution to the problem represented by the 'hole argument' in the context of general relativity, the failure of haecceitism and the suspicious nature of alleged non-qualitative metaphysical factors.[21] Crucially, RQM seems to add to the list: since it makes no sense to talk about individual physical systems and their monadic intrinsic properties and properties are essentially relative to other physical systems, the argument goes, in the context of RQM physical relations must be prior to objects and their monadic, intrinsic properties.

This is indeed Candiotto's key claim: since interactions ("between systems and instruments" (Candiotto 2017, sec. 2) and more generally between physical systems) play a crucial role in RQM, it is natural to interpret it in terms of relations, objects turning out to be mere 'nodes' in relational structures, as by now traditionally contended by ontic structural realists.

This is certainly an appealing claim, and one that echoes similar ones that can be found in several places in the literature (see, e.g., Esfeld 2004 and Muller 2011). However, we believe that, upon scrutiny, the structuralist interpretation of RQM fails. There are three basic reasons for thinking that this is the case, that we will now list in increasing order of importance.

First of all, the notion of structure is notoriously ambiguous and, lacking a precise characterization of it, not only is it difficult to understand precisely what OS amounts to. In addition, and more specifically, it is also quite complicated to establish whether the role played by relationality in the context of RQM is the same as that postulated in the context of OS. Consider the ontic characterization of information offered by Ladyman and Ross (2007) on the basis of the work of Dennett. Is this characterization sufficiently similar to what Rovelli has in mind when introducing the very idea of property-acquisition as based on the exchange of information between quantum systems? It is definitely unclear that the answer to this question should be in the affirmative. Here, at any rate, we will just mention this general worry without attempting to say anything more about the notion of (ontically loaded) relational structure.

Moving on, a second worry has to do with the extent to which RQM actually invites, so to put it, to 'structuralise' properties. In particular, it is a central assumption of OS that all physical properties are entirely relational, and even objects (may) have to be 'dissolved' in a network of relations. As anticipated above, this includes, most importantly, so-called *state-independent* properties, that is, the essential properties of physical systems that determine the sort of 'things' one is dealing with (differentiating, say, an electron from a neutron based on the fact that the former has negative charge and the latter has no charge, the fact that the former has

[21] In this case, non-empirically accessible 'primitive identities' of things.

a mass which is approximately 1840 times smaller than the mass of the latter, and so on). Now, while OSists insist, as indeed they must, that state-independent properties are structurally analysable (see Muller 2011), RQM is a theory *concerned with state-dependent properties only*: property-attributions can be (and must be) made relational only insofar as properties that depend on the state of the system are concerned. To be sure, state-independent properties are determined before any system-system interaction and are indeed presupposed as something that makes every physical system (interacting as well as non-interacting) a system of a particular *kind*.

This of course leaves it open whether a structuralist reduction of state-independent properties is possible, and we will not try to settle the matter here (for some considerations in support of a negative answer, however, see McKenzie 2020). For present purposes, it will suffice to notice that, to the extent that RQM explicitly leaves certain properties out of its relational analysis, the theory does NOT lend itself to a natural interpretation in terms of OS.[22]

Suppose that the OSist insists that at least some properties are amenable to, if not require, a structuralist interpretation. A third counterargument, and probably the most important one, is that Rovelli's emphasis on interaction is by no means to be interpreted in terms of relations being metaphysically fundamental. For, it is one thing to claim a) that relations play a fundamental role in the theory in the sense that interactions between physical systems are presented as the cause of those events that correspond to *monadic properties* acquiring definite values (relative to systems other than the property-bearer, with which the latter interacts); and a different thing to claim b) that properties and objects are literally to be regarded as derivative on *relations*, the latter being the fundamental constituents of reality. Crucially, b), but not a), requires that physical relations be regarded as basic, our metaphysical description of physical reality consequently demanding radical revision.[23] On the other hand, RQM is committed to a), but not necessarily b). The emphasis, that is, is on relationality, not relations. In connection to this, remember our earlier remarks concerning putatively different descriptions of the same event: if we were right there, it follows that on RQM there simply are no objective, system-independent, elements of reality – *not even physical relations!* - that can be the ground for the qualitative profile of everything. Rather, all (state-dependent) elements of reality are relational. To put it schematically, a typical relation such as, for instance, '...has opposite spin in the *x*-

[22] Also recall that, as mentioned at the beginning, if one concedes that things may possess properties that are not fully determinate (because of ontic indeterminacy) or not manifest (because dispositional), then even state-dependent properties – as determinables or unmanifested dispositions - could be actual yet non-relational.

[23] To use an analogy, a domain in which all things have different weights is not (at least not obviously) a domain where the fundamental constituents of reality are relations of having a weight different from something.

direction relative to…' is something different from a typical monadic but extrinsic property such as, for instance '...is spin up in the *x*-direction with respect to…'. And what RQM invites us to do is not to reduce the latter to the former, but rather to understand that all (state-dependent) properties are to be analysed in terms of the latter.

In view of the foregoing, pending further independent arguments in favour of OS, it is perfectly possible, and we think preferable, to contend that RQM, far from urging an ontology of relational structure, suggests instead an ontology of more or less 'traditional' objects and properties, which however are always dependent on one another as far as the possession of determinate properties is concerned.[24]

This means that it is advisable to understand quantum systems described by RQM as based on traditional metaphysical categories – e.g., the bundle theory of properties (Oldofredi 2021). However, there still seems to be something left to explain: what does the 'relational' in RQM refer to at the ontological level? In the next, concluding section, we put forward our own philosophical understanding of RQM and the sort of dependence it posits among quantum systems.

4. RQM, metaphysical coherentism and events

The core of our proposal is that RQM can (and perhaps should) be interpreted in terms of Metaphysical Coherentism in the sense proposed by Morganti 2019 and by Calosi and Morganti 2021), that is, in terms of the mutual ontological dependence between different entities and their properties. In a bit more detail, metaphysical coherentism is essentially a rejection of

i) The traditional foundationalist conceptions of reality in terms of levels, 'hierarchical' dependence-chains and fundamentality;
ii) The Hume-Lewis idea that fundamental entities must be absolutely independent.

Contrary to i), we suggest that RQM should be interpreted, as coherentism requires, in terms of physical systems being (at least in certain cases) mutually dependent on each other,

[24] The question remains whether the more or less traditional ontology of objects can be questioned on other grounds. In particular, one relevant worry in the present context is that objects may turn out to be 'abstractions' of sorts from physical events, something that Rovelli himself seems to suggest at times. We will discuss this in the next section.

hence not giving rise to a pyramidal hierarchy, but rather to the ontological counterpart of a Quinean web of belief, each belief/entity being interdependent with some other.[25]

As for ii), we take it that 'Hume's Dictum', according to which there are no necessary connections between distinct fundamental entities, is also straightforwardly falsified by RQM. On the one hand, at least some of the physical systems described by quantum theory are arguably fundamental. On the other, RQM clearly describes physical systems as necessarily connected to other physical systems. In particular, as far as state-dependent properties are concerned, the laws of quantum mechanics are straightforwardly interpreted as descriptions of the ways in which one system affects, and at the same time is affected by, other systems at the level of its qualitative content. In metaphysical jargon, we suggest that RQM is best interpreted as presenting physical systems as ontologically dependent on each other (i.e., symmetrically dependent) for their qualitative profiles, their mutual dependence setting constraints on possible properties that have the force of nomological necessity. Thus, it seems that metaphysical coherentism provides a natural setting for interpreting RQM.

For a very simple illustration, consider two fermions in the singlet state. Entanglement, according to the metaphysical coherentist, should be understood in terms of *contingent* mutual relations of *ontological dependence* among physical systems with respect to their *properties*. Given the singlet state:

$$\Psi = 1/\sqrt{2}(|\uparrow>_1|\downarrow>_2 - |\downarrow>_1|\uparrow>_2)$$

we can interpret it as the mereological composite of two systems 1 and 2, each one of them identified as a particular instance of a kind of thing by its distinctive state-independent properties. According to the coherentist, upon interaction systems 1 and 2 become symmetrically connected in such a way that they can only have some of the spin values that were possible before interaction. In particular, they give rise to an entangled system with total spin 0, and because of this, given Pauli's Exclusion Principle, only opposite spin values are admissible after interaction. The relevant properties, i.e., the actual spin values of the two fermions are monadic (they 'belong' to 1 or 2) yet extrinsic/relational.

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[25] An obvious objection here is that priority and dependence cannot coexist, since one contradicts the other. However, this is the case only if one assumes the asymmetry of dependence. The rejection of this assumption is exactly what is distinctive of forms of coherentism. Grounding is another matter, as one may argue that grounding is asymmetric by definition, perhaps based on its close connection with explanation. But this is not a problem for us as long as grounding is not simply a synonym of priority (if it is, then again asymmetry is no longer obvious). Incidentally, notice that in a coherentist context it is still the case that facts about symmetric dependence asymmetrically explain facts about the properties of physical systems.

Of course, the idea is that this applies generally to all physical scenarios. Consider for instance our Wigner's friend scenario. There, starting from physical system *S* in state

$$|\psi\rangle_S = a\,|\uparrow\rangle_S + b\,|\downarrow\rangle_S,$$

(see formula 1 above) a measurement performed by Wigner's friend *F* led to a determinate outcome, say, $|up_F\, |\uparrow\rangle$. Yet, from Wigner's perspective the *S*+*F* system was in state

$$a|up\ _W|up\ _F\,|\uparrow\rangle_S + b|down\ W\ |down\ F\ |\downarrow\rangle_S,$$

(see formula 5) which entails that, according to *W*, *S* does *not* have a definite spin value in the relevant direction. As mentioned, RQM solves the problem by making the attribution of the properties in question relative to physical systems. This, we now claim, attributes to physical systems exactly the features postulated by metaphysical coherentism. In particular:

1) The system *S* does not have a determinate spin on its own, yet it does have a determinate spin value with respect to *F* and/or *W*, which means that *S* is dependent on *F* and/or *W* with respect to its qualitative profile;
2) The dependence in question is symmetric: insofar as their report of *S*'s properties is regarded as one of their qualitative features, *F* and *W* are dependent on *S* for their qualitative content; generalizing, every interaction modifies the state of the interacting entities.[26]

Two remarks are in order at this point. First, one may object that, since it is a metaphysically thick, realist view, coherentism does not mesh well with the claim that (state-dependent) properties have no objective, absolute values. However, the perspective-relativity of dependence is not an issue for the coherentist, as long as the dependence relations in question are symmetric, which we argued is the case. More generally, it is simply incorrect to take metaphysical realism to imply, or coincide with, objectivism about things, properties, facts etc.[27] Secondly, one could complain that coherentism does not explain the perspective-relativity of dependence. This is certainly the case, yet we do not think this is an issue for our proposal. Indeed, the key interpretative issue raised by RQM, or at any rate the one we aimed

[26] This goes to confirm a point raised above *a propos* the symmetric flow of dependence and information between a measuring system and the measured one. Speaking of which, it is perhaps worth pointing out that, according to the coherentist understanding of RQM, for a system *S* to be entangled means that *S* depends on an external system, from the perspective of which *S* appears composed of *n* subsystems which are mutually related with respect to their qualitative profiles. Questa non l'ho capitaAn interesting relational aspect of ontological dependence emerges, which however will have to be discussed on some other occasion.

[27] There is a connection here with the ambiguity in the use of the term 'realism' in connection to quantum mechanics, variably taken to mean objectivity, observer-independence, absoluteness of values, classical ontology of particles and more.

to tackle in the present paper following the extant literature, does not have to do with the origin of its characteristic perspectival nature, but rather with the ontological status that should be attributed to physical systems and their properties if one takes RQM to be the (approximately) correct description of the world, and consequently accepts relationality as a fact.

Before closing, there are a couple of other questions that need to be addressed. First of all, how is coherentism better than, or even just different from, the ontological interpretations that we have already considered – i.e., monism and structuralism?

The answer to this question is straightforward. The proposed coherentist construal is more plausible than priority monism because the postulation of a symmetric dependence between proper parts of the universe by no means entails that the whole is (asymmetrically!) prior to the parts – which, as we have seen, is an untenably strong claim. Also, the proposed coherentist construal is more plausible than structuralism because hypothesizing ontological dependence relations between physical systems by no means entails that those physical relations are more fundamental than objects with their monadic properties.[28]

Consequently, the coherentist can provide an explanation of the essential relationality of RQM without incurring the costs of an ontology of physical relations – which, as we have seen, requires that the structuralist analysis be carried over in contexts where physics may not justify it. Even granting that OS and coherentism were equally physically grounded, which in fact we provided reasons for doubting, the following claim should be noted. While OS reifies the explanans, since (interactions are literally fundamental constituents of reality) coherentism takes the empirical evidence to urge a change in the form of explanation since interactions are essential for a complete description of the way in which the fundamental constituents give rise to reality

One last open question concerns the connection (if any) between the coherentist view of RQM and the idea of an ontology of events, or 'flashes'. As illustrated, for instance, by Allori (2015), so-called primitive ontologies are increasingly popular in the philosophy of quantum mechanics. In a nutshell, these aim to extract from the theory a description of some fundamental structure of matter in three dimensions. According to flash ontology, for instance, this fundamental structure is one of local events in space-time.[29] While usually developed in the

[28] One may object that exactly the same holds for moderate OS, the view that relations and objects are equally fundamental. Notice, however, that, as we explained earlier, an essentially relational ontology is not the same as an ontology that gives a fundamental role to relations. In a nutshell, the difference is that moderate OS posits two fundamental categories (objects, relations) and some symmetric dependence relations holding among tokens of each; coherentism, instead, only posits one fundamental category (objects), and symmetric dependence relations holding among tokens of it.

[29] For an interpretation of quantum mechanics centered on events, see Dorato (2015).

context of collapse interpretations (flashes corresponding to the spontaneous collapses that replace superpositions with determinate states), the flash ontology might also be plausibly regarded as the natural framework for RQM: the basic events, in this case, would be those corresponding to local interactions between physical systems, determining the (perspectival, relative) state-dependent properties of those systems.

Now, there may seem to be a tension at this point between the coherentist claim that on RQM physical systems and their properties fundamentally depend on each other, and the claim, sometimes explicitly endorsed by Rovelli himself (see, e.g., Laudisa and Rovelli 2021, introduction), that the basic ontological entities are events of the form 'system *S* acquires property *P* with respect to system *Q* (and conversely) at a certain time *t*'. The tension consists in the fact that, on the former construal, physical systems and their properties are fundamental, and events involving them are derivative. On this understanding, events are a byproduct of interactions between physical systems that in the theory are presented as the *cause* of the determinateness of the system's monadic properties (relative to systems other than the property-bearers). On the latter construal, instead, the opposite would be the case: events as the basic inhabitants of the space-time four-dimensional continuum would be basic, and objects/physical systems/substances and their properties would be derivative.

While we acknowledge the significance of this issue, however, we think it is not essential to settle the matter here. In fact, we take it to be nearly impossible, as a number of additional open problems would have to be dealt with, having to do with the relationship between relativity and quantum mechanics, the prospects of various hypotheses concerning quantum gravity, the metaphysics of space, time, objects and persistence and more.

As things stand now, at least for present purposes, we think it is sufficient to point out that a systematic 'translation' between the two views might be possible. That is, talk of physical systems exhibiting properties and being ontologically dependent on other physical systems for their ontological profile (at any particular time *t*) can always be turned into talk of events of the form '*S* acquires property *P* in relation to *Q* – and *Q* acquires property *R* in relation to *S* - at time *t* in virtue of the mutual ontological dependence between *S* and *Q*. The converse translation, is of course, also entirely possible. The former translation may be more useful when one wants to emphasise the role of interaction and its outcomes from a spatio-temporal, hence relativistic, point of view. The latter may instead be more appropriate when one aims to move from a description of the physical content of specific points/regions of space-time to a more traditional ontology of persistent things and their properties. On this, however, RQM need not (and indeed should not be expected to) establish any order of metaphysical priority.

Conclusions

In this paper, we have identified and critically compared some proposals that can be advanced to clarify the ontological consequences of Relational Quantum Mechanics. Focusing first on the more popular ones, we started by discussing priority monism and ontic structural realism and argued that these views are not suitable for defining an ontological interpretation of the theory. Monism is unable to account for the sort of mutual and symmetric dependence exhibited by the proper parts of the universe, and for the seeming non-epistemic dependence of the cosmos on its proper parts. As for ontic structural realism, besides being notoriously vague on the key notion of relational structure, it seems to unwarrantedly move from Rovelli's emphasis on interactions between physical systems to the claim that reality is at root *wholly* analysable in terms of physical relations. Starting from these negative results, we endorsed an alternative that we regard as more promising, based on so-called 'metaphysical coherentism'. We suggested that metaphysical coherentism, with its emphasis on symmetric ontological dependence between more or less traditional objects and properties, makes it possible to achieve the best of both worlds: that is, to make relationality metaphysically fundamental while at the same time not requiring a seemingly impossible, or at least implausible, structuralist reduction of everything physical. At the same time, however, we left it open whether the truly fundamental ontology of RQM is one of events, or 'flashes', in space-time. On this alternative construal, we suggested, the fundamentalia would change (spatio-temporally localized events rather than three or four-dimensional continuants with their properties) but the essential relationality, i.e., ontological interdependence, of the physical contents of reality would not be affected. Given this and the intertranslatability of event talk and object talk, we take it, the coherentist emphasis on symmetric dependence is in any case the most plausible way to pick out the essential, revolutionary message of RQM.

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