Measurements and Elements of Reality in Relational Quantum Mechanics

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Introduction

In 1996, Carlo Rovelli proposed a novel point of view about the physical meaning of quantum theory, namely the relational interpretation of quantum mechanics. The core idea of this novel interpretative framework consists in a rejection of the notion of 'absolute state' of a physical system and to regard its physical descriptions as being fundamentally relative.[1] According to the relational interpretation, a physical event happens when two physical systems interact with each other and the descriptions of such an interaction is relative to the system involved. It is claimed that relational quantum mechanics can address and solve a number of confusing puzzles at the core of the foundations quantum mechanics, in particular the so-called 'measurement problem' and the problem of locality in the EPR scenario.

The measurement problem takes different forms: it is a general heading for a number of related interpretational issues.[2] It is usually presented as the incompatibility between the following three claims: (i) the quantum state is complete: it specifies all the physical properties; (ii) the quantum state evolves linearly according to the Schrödinger equation; (iii) measurements on a certain physical quantity of a particle have determinate outcomes.[3] These claims are incompatible because if we accept claims (i) and (ii), then the linear evolution of the quantum state does not specify a unique measurement outcome. Therefore, one of these claims must be discarded: which one of these claims must be discarded depends on the particular interpretation of quantum mechanics that one relies on.

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[1] C. Rovelli, 'Relational Quantum Mechanics', *International Journal of Theoretical Physics* 35.8 (1996): 1637-1678.

[2] The following paragraph is meant to give a general introduction to the measurement problem, but it is by no means a detailed exposition (as it goes beyond the scope of the thesis). For further literature and a more precise characterization of the measurement problem, I refer the reader to: T. Maudlin 'Three measurement problems'. *Topoi* 14**,** 7–15 (1995)

[3] O. Lombardi and D. Dieks, 'Modal Interpretations of Quantum Mechanics', *The Stanford Encyclopedia of Philosophy* (Winter 2021 Edition), Edward N. Zalta (ed.), URL = https://plato.stanford.edu/archives/win2021/entries/qm-modal/

Another related aspect concerns the applicability of quantum theory to the measurement process itself: since the measuring apparatus or observer is a physical system, it should be possible, in principle, to treat the measurement interaction as quantum-mechanical.[4] In other words, how can we draw an unambiguous boundary between microscopic reality and macroscopic reality? What distinguishes measurement interactions from ordinary physical interactions?

According to Rovelli's relational interpretation of quantum mechanics any physical interaction between any physical system counts as a 'measurement'.[5] A physical system possesses definite physical properties (for example, a definite value of spin of a particle) with respect to another system only at the time of their interaction: systems have no well-defined physical properties outside of their physical interaction between each other.

Furthermore, this characterization of 'measurements' allows relational quantum mechanics, as it has been claimed by certain authors, to maintain locality in accounting for the EPR correlations in the sense that two distant systems cannot have instantaneous, faster-than-light physical influence between each other because they cannot be both real from the perspective of an observer, since he cannot interact with two distant physical systems at the same time.[6]

In a recent paper, it has been claimed that all events that are physically real relatively to an observer must be located within an observer's causal past (or past light-cone) in force of the claim that an observer needs to interact with a given system in order to account for its 'reality'.[7] Specifically, the authors claim to maintain Bell's principle of local causality, which states that "The direct causes (and effects) of events are near-by, and even the indirect causes

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[4] G. Bacciagaluppi and A. Valentini. *Quantum Theory at the Crossroads*, p. 143.

[5] C. Rovelli, 'The Relational Interpretation of Quantum Physics', *arXiv preprint arXiv:2109.09170* (2021).

[6] M. Smerlak and C. Rovelli, *Relational EPR*.

[7] P. Martin-Dussaud, C. Rovelli and F. Zalamea, 'The Notion of Locality in Relational Quantum Mechanics', *Foundations of Physics* 49.2 (2019): 96-106.

(and effects) are no further away than permitted by the speed of light."[8] The authors state that the problem of locality depends on what are the 'beables') of a theory (that is, the elements of reality according to a theory), which depend on the particular interpretation that one assumes.[9]

In this thesis, I claim that Rovelli's characterization of measurement implicitly presupposes that we can make a distinction between 'direct' and 'indirect' measurements in quantum mechanics and he appears to rely on the idea that measurements should be understood, properly speaking, as 'direct' measurements, namely that a 'measurement' simply consists, in any case, in a single physical interaction between the observing system and the system of interest. However, I will show in the course of my thesis that the notion of 'direct' measurements is not the proper one to understand measurements in quantum mechanics. To show this, I will rely on Bohr's analogy between the single- and double-slit experiments and its further analogy with Hermann's treatment of the γ-ray microscope.[10]

Furthermore, by implementing Hermann's idea of retrospective causality (I will show that Hermann's ideas are compatible with Rovelli's in his relational interpretation), I claim that elements of reality (in other words, what an observer considers as physically real with respect to himself) need not be exclusively confined within an observer's past light-cone. In the EPR scenario, Alice can consider Bob's particle in a distant region B as physically real with respect to herself: by holding on to the notion of indirect measurements, Alice uses her particle as an auxiliary system to measure Bob's. I argue that Alice can ascribe an element of reality to the event in the distant region B because after she measures a physical quantity on her particle, she can reconstruct (at least in principle and always in retrospection) a causal succession of events

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[8] J. Bell and A. Aspect, 'La nouvelle cuisine'. In *Speakable and Unspeakable in Quantum Mechanics: Collected Papers on Quantum Philosophy*, Cambridge: Cambridge University Press. (2004): 232-248, p. 239. doi:10.1017/CBO9780511815676.026

[9] P. Martin-Dussaud, C. Rovelli and F. Zalamea, 'The Notion of Locality in Relational Quantum Mechanics', p. 2.

[10] See: G. Bacciagaluppi, 'Did Bohr Understand EPR?', (2014); G. Bacciagaluppi, 'Bohr's slit and Hermann's microscope.' *Grete Hermann-Between Physics and Philosophy.* Springer, Dordrecht, (2016), 135-147.

that explains the outcome of her measurement and such retrospective causal analysis allows her to extend the element of reality to the event in region B, without violating locality.

This thesis will be structured as follows. In section 1, I characterize in detail the relational interpretation of quantum mechanics and the EPR correlations as treated from the perspective of this framework. In section 2, I will introduce Bohr’s complementarity relying on Don Howard’s reconstruction. I will then explain the analogy between the single- and double-slit experiments in Bohr’s reply to the EPR paper and highlight Bohr’s implicit idea that there is no difference between the EPR case and the single-particle case. In section 3, I present Grete Hermann’s ideas about the relative character of quantum-mechanical descriptions and her treatment of the γ-ray microscope, which also realizes an EPR scenario. I will furthermore compare Hermann and Rovelli’s core ideas to show that they share similar views concerning the fundamental relativity of quantum-mechanical descriptions and that Hermann’s retrospective causality can be implemented in Rovelli’s relational interpretation and may enrich the notion of causality at use in relational quantum mechanics. In section 4, I elaborate my claim that in the EPR scenario, elements of reality can be retrospectively ascribed to events taking place outside an observer’s past light cone. In section 5, I then compare Hermann’s view with a modern approach proposed by Alexia Auffèves, namely the ‘Contexts, systems and modalities’ approach.

Section I – The Relational Interpretation of Quantum Mechanics

1.1 An Introduction to Relational Quantum Mechanics

In this subsection, I introduce the relational interpretation of quantum mechanics and explain its core features. For this purpose, I will mostly rely on Rovelli's original work of 1996 on the relational interpretation.[11] When necessary, I will consider more recent works where he has clarified some subtler aspects of his interpretation.

The main features that characterize the core of the relational interpretation of quantum mechanics that I will present in detail are the following:

1. The idea that the notion of 'state' encodes the properties that two physical systems assume when they interact with each other, not to a single system when left to itself;
2. A quantum state is only a theoretical tool used to make calculations: what we should be 'realists' about in this framework are variables of physical systems that take values when systems interact with each other, not quantum states;
3. The natural world is quantum-mechanical: even if terms such as 'observer' or 'measurement' often feature in the relational interpretation, they do not denote any kind of 'special system' (for instance, a conscious physicist, or a system that has an inherently classical status) nor any sort of special physical process that somehow should be fundamentally distinguished from others (for example, in relational quantum mechanics any physical interaction between systems is to be counted as a 'measurement', without requiring that a process of measurement involves a microscopic particle interacting with a classical measuring device: both are quantum-mechanical in nature);

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[11] C. Rovelli, 'Relational Quantum Mechanics'.

4. Quantum mechanics is a complete theory: relative to an observer, the quantum-mechanical description that this observer gives of a physical event exhaust all that there is to be said about the reality of the physical event in question. As we shall see, these considerations imply that from the perspective of the relational interpretation, the underlying ontology is characterized by 'sparse, relative facts' and as such, it is in contrast with a 'strong' reading of realism. Let us start by presenting the original motivations on which the relational interpretation is based.

Rovelli begins his work of 1996 by pointing out that the notion of 'absolute, observer-independent state' of a physical system is generally uncritically assumed and leads to several interpretational problems. He explicitly rejects this notion and maintains that physical states of systems are always relative states. As Rovelli states in introducing his article in 1996:

> The thesis of the present work is that by abandoning such a notion (in favor of the weaker notion of state – and values of physical quantities – *relative* to something), quantum mechanics makes much more sense. This conclusion derives from the observation that the experimental evidence at the basis of quantum mechanics forces us to accept that distinct observers give different descriptions of the same events. From this, I shall argue that the notion of observer-independent state of a system is inadequate to describe the physical world beyond the $\hbar \rightarrow 0$ limit, in the same way in which the notion of observer-independent time is inadequate to describe the physical world beyond the $c \rightarrow \infty$ limit. I then consider the possibility of replacing the notion of absolute state with a notion that refers to the relation between physical systems.[12]

More precisely, Rovelli criticizes the idea that 'states' (and all properties of physical systems) should be understood as referring to a physical system alone, in the sense that a system has a certain physical state and 'possesses' physical properties at any instant of time independently of any other physical system. The state of a physical system is always a 'relative state' in the sense that the properties encoded in it are relational properties of two systems that physically interact with each other.

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[12] C. Rovelli, 'Relational Quantum Mechanics', p. 1

The main reason for rejecting the notion of 'absolute state' of a physical system is based on the observation that, "in quantum mechanics, different observers may give different accounts of the same sequence of events."[13] To motivate this observation, Rovelli gives the example of two distinct observers, *O* and *P*, that describe the measuring process of certain physical quantities (for example, the spin of a particle) of a system *S* differently. Observer *O* 'measures' the spin of a system *S* and has a certain probability of obtaining either the value 'spin-up' or 'spin-down' Observer *O* physically interacts with *S* to measure its spin and obtains 'spin-up'. Therefore, *O* will update the state of *S* ('update' because the quantum state is understood as a formal device used by the experimenter, and not something that 'belongs' to the system), at time T^2 (when the measurement is performed) to $|1\rangle$. Observer *P* did not interact with either *O* or *S* (but knows their respective initial states), therefore at time T^2 (when *O* measures *S*), *P* will describe the interaction between *O* and *S* by attributing a quantum state jointly to *O* and *S*: the linearity of quantum mechanics implies that with respect to *P*, the combined system *S*-*O* is in a superposition of states, one in which *O* has obtained $|1\rangle$ when measuring *S* and one in which *O* has obtained $|1\rangle$ (what 'superposition' means in this framework is precisely that from the point of view of *P*, there is a correlation to be expected between *O* and *S*). In formal terms, the description that *O* gives of the measuring process is:

$$T^1 \rightarrow T^2$$

$$\alpha|1\rangle + \beta|2\rangle \rightarrow |1\rangle$$

The descriptions that observer *P* gives of the measuring process is:

$$T^1 \rightarrow T^2$$

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[13] C. Rovelli, 'Relational Quantum Mechanics', p. 4.

$$(\alpha|1\rangle + \beta|2\rangle) \otimes |\mathrm{Init}\rangle \rightarrow \alpha|1\rangle \otimes |O1\rangle + \beta|2\rangle \otimes |O2\rangle$$

As we can see, *O* and *P* are giving different descriptions of the same measurement process.[14] To questions like 'which of these descriptions is the correct one?' or 'is there a more 'complete' underlying description of this measurement process that may tell us what is 'objectively' happening in reality?' Rovelli would reply that these are meaningless questions: both the descriptions of the observers *P* and *O* are exhaustive and correct accounts of what is happening 'in reality' in the measurement process. He explicitly dismisses the 'thesis of the incompleteness of quantum mechanics' and claims that: "*Quantum mechanics is a theory about the physical descriptions of physical systems relative to other systems, and this is a complete description of the world*."[15]

Even if quantum-mechanical descriptions are complete relatively to a given observer and different observers can give different accounts of the same physical process, a comparison between the accounts relative to different observers is possible, but only through a physical interaction between them. Two physicists can share results by communicating with each other, but communication ultimately involves a physical interaction between particles: one important idea that characterizes the relational interpretation is that there is no classical world properly speaking: the natural world is ultimately quantum-mechanical.[16]

A second important point in the relational interpretation is that the 'quantum state' or 'wavefunction' of a system not only is observer-dependent: it is not understood as a real 'entity' either. It is simply regarded as a useful mathematical tool and, as such, it has no physical meaning. As Rovelli explains in a more recent paper titled 'Space is Blue and Birds fly Through It', the concept of 'wavefunction' was originally introduced by Erwin Schrödinger in 1926.

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[14] C. Rovelli, 'Relational Quantum Mechanics', p. 3.

[15] C. Rovelli, 'Relational Quantum Mechanics', p. 7.

[16] C. Rovelli, 'Relational Quantum Mechanics', p. 8.

Rovelli explains that with the introduction of the wavefunction, Schrödinger changed the algebraic language of quantum mechanics by using differential equations, which were more familiar to physicists and easier to work with. However, Schrödinger also took a conceptual step, which Rovelli claims to have been highly misleading: this step is entirely interpretational and it does not add to the predictive power of the theory:

> The *conceptual* step was to introduce the notion of "wave function" ψ, soon to be evolved into the notion of "quantum state" ψ, endowing it with heavy ontological weight. This conceptual step was wrong, and dramatically misleading. We are still paying the price for the confusion it has generated.[17]

This elucidates what, according to the relational interpretation, quantum mechanics is about: it is not about the dynamics of the wavefunction as a real physical entity from which the observed world emerges, but is about physical facts: in other words, it is a theory about physical variables of physical systems that take values when these interact with each other.[18]

Therefore, Rovelli urges us to avoid any ontic commitment concerning the quantum state and to understand it as nothing more than a mathematical device we use to make predictions about which values the variables of physical systems will assume when interacting, from the perspective of another system. To quote Rovelli's words:

> In RQM, the quantum state is not a representation of reality: it is always a relative state and is only a mathematical tool used to predict probabilities of events *relative to a given system*. The quantum state of a composite system relative to an external system is not an account or record of relative events *between the subsystems* of the composite system. It is only a mathematical tool useful for predicting probabilities of events *relative to the external system*.[19]

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[17] C. Rovelli, 'Space is Blue and Birds Fly Through it', *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 376.2123 (2018): 20170312, p. 1.

[18] C. Rovelli, 'Space is Blue and Birds Fly Through it', p. 2.

[19] A. Di Biagio and C. Rovelli, 'Relational Quantum Mechanics is about Facts, not States: A reply to Pienaar and Brukner', *arXiv preprint arXiv:2110.03610* (2021), p. 1.

The idea underlying the relational interpretation is that we can have a naturalistic view of the physical world without postulating conscious observers, collapse processes, or introducing a classical/quantum bipartition of the physical world. More precisely, Rovelli claims that his interpretation takes its roots from the 'Copenhagen interpretation', where the reality of physical events is observer-dependent: a physical fact becomes actual when it is observed.[20] The important difference is that Rovelli uses the term 'observer' to refer to any physical system to which we relativize the quantum description: any arbitrary physical system can be labeled as 'observer'. There is no 'cut' (in the sense of Heisenberg) that separates the classical and the quantum reality. Macroscopic objects have no intrinsic classical status because they are composed of microscopic particles that obey quantum mechanics.[21] Therefore, to state that a fact becomes actual when it is observed means that it becomes physically real upon any interaction between any physical systems, and the reality of such a fact is relative to the interacting systems. Terms such as 'measurement' or 'observation' mean no more than this: Rovelli claims that Heisenberg was right in maintaining that reality is 'observer-dependent', but he did not recognize that the 'observer' need not necessarily be a macroscopic entity. The role of the 'Copenhagen observer' is not limited to systems belonging to the macroscopic, classical world, but can be assumed by any physical system.[22]

However, in comparing RQM with the Copenhagen interpretation, it is important to highlight, following Don Howard, that the Copenhagen school is not a circle of thinkers who all share the same views on 'observers' and the cut between classical and quantum reality.[23] This is important because, especially in his 1996 paper, Rovelli refers to Bohr as applying a

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[20] Strictly speaking, following Don Howard's reconstruction of Bohr's doctrine of classical concepts, we should take Rovelli as referring to Heisenberg rather than the Copenhagen circle as a whole.

[21] In 'Stable Facts, Relative Facts' Di Biagio and Rovelli discuss 'stable facts': facts that become stable, meaning that we can disregard their relativity, thanks to decoherence. I will address 'stable facts' in section V.)

[22] F. Laudisa and C. Rovelli, 'Relational Quantum Mechanics', https://plato.stanford.edu/archives/win2021/entries/qm-relational/

[23] D. Howard, 'Who invented the "Copenhagen Interpretation"? A study in mythology.' *Philosophy of Science* 71.5 (2004): 669-682, p. 670.

‘cut’ between the microscopic system to be measured (which is treated quantum-mechanically) and the macroscopic ‘measurement apparatus’ or ‘the physicist’ in a laboratory, which are described classically. Although I will elaborate more extensively on this point in the second section of my thesis, I wish to point out that, following Howard’s work, I take Rovelli to refer to Heisenberg rather than to Bohr, in that Rovelli wrongly commits Bohr to Heisenberg’s views about the role of the observers and the placement of the ‘cut’ between the microscopic system and the macroscopic classical apparatus.

I conclude this subsection by presenting the ontology of relational quantum mechanics and in which sense it is claimed that relational quantum mechanics embraces a realist standpoint about the physical world. As explained earlier in this section, the quantum state has no ontic significance, therefore the relational interpretation is based not upon an ontology of ‘states’ (which have no physical meaning) but upon ‘facts’, or variables that take values when two physical systems interact with each other. Physical events are actualized through interaction between two physical systems and the ‘actuality’ of these facts is relative to the systems involved in the interaction. Therefore, the relational interpretation is based upon “a sparse ontology of (relational) quantum events happening at interactions between physical systems.”[24] Events simply consist in physical interactions between two systems. As such, the relational interpretation conflicts with a ‘strong’ realist understanding of reality, according to which physical systems possess definite properties (equivalently, physical variables of systems have certain definite values) at any instant of time, independently of any other system. Instead, from the perspective of the relational interpretation, it is claimed that there is no additional or deeper description of physical reality that allows for an ‘objective’ comparison between descriptions relative to different observers.

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[24] C. Rovelli, ‘Space is Blue and Birds Fly Through It’, p. 5.

However, relational quantum mechanics is not committed to solipsism (in the sense that only my mental states are ‘real’ and there is no ‘objective’ reality in any sense of the term) because it does embrace what Rovelli calls a ‘weaker’ form of realism, namely that there is a reality independently from my mental states (which, ultimately, are also reducible to particles that interact and obey the laws of quantum mechanics). Rovelli uses the term ‘weak realism’ to point out that in his view, systems do have properties, but they depend on the perspective of a physical system. In contrast, ‘strong realism’ (as Rovelli named it) would presuppose that properties are ‘observer-independent’, that is, they do not depend on other physical systems. Values of variables of any physical system are relational, that is, relative to another system with which they have interacted.[25]

Therefore, it is claimed that what is real is not reduced to the mental states of a conscious observer. Facts are real in the sense of being ‘out there’, but their reality is always relative to some other system. The relational interpretation embraces a form of ‘weak realism’, where ‘facts’ happen each time there is an interaction between physical systems, and the ‘reality’ of these facts is relative to these interacting systems because the notion of ‘observer-independent state’ of a system is rejected:

> ‘Realism’ is a term used with different meanings. Its weak meaning is the assumption that there is a world outside our mind, which exists independently from our perceptions, beliefs or thoughts. Relational QM is compatible with realism in this weak sense. “Out there” there are plenty of physical systems interacting among themselves and about which we can get reliable knowledge by interacting with them […].

An important consequence of this philosophical perspective about ‘reality’ is with respect to the EPR case: since Alice and Bob are not physically interacting with each other when they measure the spin (or the position or momentum) of their respective particles in spacelike

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[25] F. Laudisa and C. Rovelli, ‘Relational Quantum Mechanics’, https://plato.stanford.edu/archives/win2021/entries/qm-relational/

separated regions, the two interactions cannot be directly compared, unless Alice and Bob 'causally' meet, that is, they physically interact with each other to communicate results.

In the next subsection, I will discuss in detail how relational quantum mechanics claims to give a local account of EPR correlations.

1.2 The EPR Correlations in Relational Quantum Mechanics

In this subsection, I analyze the problem of locality and the EPR scenario in the relational interpretation. Rovelli and other authors have extensively discussed the EPR scenario in two papers, 'Relational EPR' and 'The Notion of Locality in Relational Quantum Mechanics'. The first of these papers specifically discussed how the EPR correlations can be understood as challenging the notion of 'strong' realism rather than 'locality'. In the second paper, Bell's notion of 'local causality' is discussed within the framework of relational quantum mechanics. In this discussion, 'locality' is understood as the impossibility of two spacelike separated physical events to instantaneously interact with each other (in other words, they should not have any faster-than-light physical influences on each other).[26]

Let us start with the treatment of the EPR scenario from the perspective of the relational interpretation. The important point of the paper 'Relational EPR' is that within the framework of relational quantum mechanics, the EPR correlations can be interpreted as a challenge to Einstein's strong realism rather than to locality as an essential feature of the physical world. In Einstein's words: "*there exists a physical reality independent of substantiation and*

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[26] For further literature on the notion of locality in relational quantum mechanics which I will not explicitly discuss in this thesis, see: F. Laudisa, 'The EPR argument in a relational interpretation of quantum mechanics', *Foundations of Physics Letters* 14.2 (2001): 119-132; F. Laudisa, 'Open problems in relational quantum mechanics', *Journal for General Philosophy of Science* 50.2 (2019): 215-130; Q. Ruyant, 'Can we make sense of Relational Quantum Mechanics?', *Foundations of Physics* 48.4 (2018): 440-455;

perception."[27] The authors claim that RQM can locally account for the EPR correlations by departing from such an assumption because physical reality always requires physical interaction between an observer and an observed system. Therefore, two distant events cannot be simultaneously real for a given observer:

> […] Locality constitutes, therefore, the base of the relational methodology: an observer cannot, and must not, account for events involving systems located out of its causal neighbourhood (or light-cone).[28]

Let us formulate this point in the usual scenario involving Alice and Bob each performing a measurement on their respective particles in spacelike separated regions, that were initially prepared in the singlet state. Alice and Bob prepare the composite system α+β in the singlet state: they interact with the composite system and measure the square of the total spin. That is, Alice and Bob have information that the total spin of α+β equals zero.[29]

When Alice and Bob perform a measurement of spin on their respective particles in spacelike separated regions, Alice's outcome cannot be said to be 'real' (in the sense of Einstein) with respect to Bob (and vice-versa). These are different contexts that cannot be directly compared. If Alice's outcome cannot be said to be a real event with respect to Bob, what is the meaning of the correlations entailed by the wavefunction? The authors answer that such correlations do not say anything about the 'absolute' state of affairs of the world. As I explained, the idea of an absolute state of affairs of the natural world is rejected in RQM: this would imply the existence of a preferred context (or, as Smerlak and Rovelli put it, supposing that there is an absolute state of affairs would presuppose the existence of a nonlocal, 'super-observer' that can instantaneously measure the spin of the two particles A and B).[30] In force of

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[27] M. Smerlak and C. Rovelli, 'Relational EPR', *arXiv preprint quant-ph/0604064* (2006), p. 5.
[28] M. Smerlak and C. Rovelli, 'Relational EPR', p. 3.
[29] M. Smerlak and C. Rovelli, 'Relational EPR', p. 6.
[30] M. Smerlak and C. Rovelli, 'Relational EPR', p. 5.

this claim, such correlations cannot be interpreted as a sort of physical influence between two spacelike separated events:

> Contradiction emerges only if, against the main stipulation of RQM, we insist on believing that there is an absolute, external account of the state of affairs in the world, obtained by juxtaposing actualities relative to different observers.[31]

Bob may use the wavefunction, after he has measured the spin of his particle and found 'spin up', to predict which outcome Alice will communicate to him once they are back in causal contact or when Bob goes to region B to measure the spin of Alice's particle himself. There is no violation of locality, because he needs to be in causal contact with Alice or the particle in order to ascribe an element of reality to the outcome of the measurement on the spin of Alice's particle, but this cannot be done before they physically meet, otherwise we could interpret the correlations as a faster-than-light physical influence between the two measurements.

Therefore, if one embraces the perspective proposed by the relational interpretation and consequently a weak form of realism, it is possible to locally account for the EPR correlations because Alice cannot ascribe an element of reality to a physical event taking place in Bob's region: whether a physical event is real or not always depends on the perspective of a physical system that assumes the role of 'observer'.

In another recent paper, 'The notion of Locality in Relational Quantum Mechanics', Martin-Dussaud, Rovelli, and Zalamea have argued that the meaning of 'non-locality' depends on what are the 'beables' of the theory (Bell's concept for 'elements of reality' of a theory) from the perspective of a particular interpretation of quantum mechanics.[32] In the case of the relational interpretation, the reality of an event depends on the perspective of an observer, therefore Bell's notion of 'beables' is replaced with one of 'relational beables' and make

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[31] M. Smerlak and C. Rovelli, 'Relational EPR', p. 7.

[32] P. Martin-Dussaud, C. Rovelli and F. Zalamea, 'The Notion of Locality in Relational Quantum Mechanics', p. 2.

explicit the claim that all elements of reality from the perspective of an observer must be located within the observer’s causal past (or past light-cone):

> […] if one sticks to a particular observer, a relational beable is nothing but a quantum event. It will not be as absolute as Bell would have expected, because talking about ‘quantum events’ still requires us to first fix a reference observer, but a beable can still be conceived as an ‘element of reality with respect to the reference observer’. Now, given a reference observer *O, the only physically meaningful beables lie in the past cone of O.*[33]

Subsequently, the authors bring a new important point forward and introduce the notion of ‘common cause’ to explain the EPR correlations: an observer that is located in this common region will see correlations between the outcomes of Alice and Bob because he concludes that there is a ‘common cause’ in the common past of the two outcomes. To show this, Martin-Dussaud et al. give the example of a radioactive particle that can be detected by either detector A or detector B (which is analogous to the EPR case so far discussed). Say A flashes to signal that it has detected the radioactive particle, which is seen by observer *O* lying in a common region of the future light-cones of A and B:

> […] if the observer *O* sees a light signal from A, he will think that the radioactive particle in the region of the past cone Λ is the cause of the detection of an α particle in A. The same thing could also be said symmetrically for B. Neither causes nor effects travel faster than light whatsoever. There are correlations between A and B because there is a common cause in their common past.[34]

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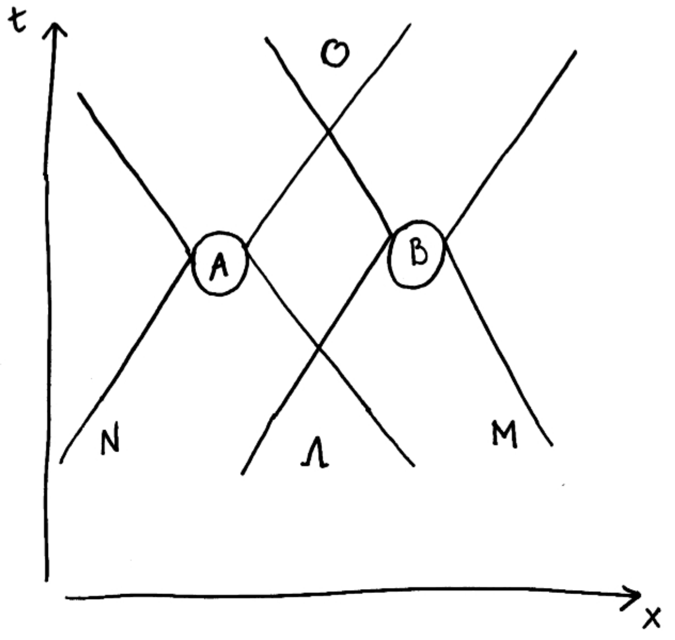
[33] P. Martin-Dussaud, C. Rovelli and F. Zalamea, ‘The Notion of Locality in Relational Quantum Mechanics’, p. 4.

[34] P. Martin-Dussaud, C. Rovelli and F. Zalamea, ‘The Notion of Locality in Relational Quantum Mechanics’, p. 5.



(Fig. 1: A visual representation of the EPR scenario with light-cones).[35]

However, the authors do not give a precise formulation of the notion of ‘common cause’ here involved: it is only mentioned that we do not have to understand the notion of ‘common cause’ as tied to determinism (because, from the perspective of the relational interpretation, quantum mechanics is fundamentally an indeterministic theory):

> With the relational interpretation, the possible weirdness of non-local experiments boils down to the weirdness of indeterminism. […] In fact, ‘non-locality’ exemplifies the difficulty to understand together ‘causality’ and ‘indeterminism’ in the same conceptual and mathematical framework.[36]

I now conclude this section by summarizing the essential point of the relational interpretation of quantum mechanics that I have discussed and introducing the main claim of this thesis.

The main observations on which RQM is based are the completeness of the quantum-mechanical descriptions of an event (relative to an observer) and that different observers may

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[35] P. Martin-Dussaud, C. Rovelli and F. Zalamea, ‘The Notion of Locality in Relational Quantum Mechanics’, p. 4.

[36] P. Martin-Dussaud, C. Rovelli and F. Zalamea, ‘The Notion of Locality in Relational Quantum Mechanics’, p. 4.

give different descriptions of the same sequence of events. From this, Rovelli concludes that if these observations are true, then it follows that there is no ‘observer-independent’ description of a physical event, and this is the best description we can give of such an event (there are no underlying ‘hidden variables’ that may tell us what is the ‘absolute’ or ‘observer-independent’ state of the system). Therefore, he proposes to replace the notion of ‘quantum state’ understood as referring to a system alone, with the notion of ‘relative state’, that is, a state that refers to two systems involved in an interaction. However, the ‘quantum state’ carries no ontological significance in relational quantum mechanics: according to Rovelli, quantum mechanics is a theory about (relative) facts, not about ‘states’, as these are only formal tools through which we register the outcomes of past interactions with a physical system and that we use to predict, probabilistically, the future values that the variables of such systems will take when we will interact again, in a certain manner, with it.

Furthermore, by claiming that the world has a quantum-mechanical nature, in the sense that all physical systems are composed of microscopic particles (quantum systems) which are ‘on a par’ and ultimately obey the laws of quantum mechanics, Rovelli solves the measurement problem in RQM (at least one aspect of it, namely the problem of distinguishing certain physical processes, which would correspond to ‘measurements’, from other kinds of physical interactions) by claiming that any physical interaction between systems counts as a measurement, where any system involved in the interaction can be arbitrarily labeled as ‘observer’. In this sense, physical variables of systems take values when they interact with other systems, and such values are actualized relative to the ‘observer’ system, but such values cannot be said to be ‘actual’ with respect to a third system that has yet to interact with the systems in question.

Finally, the EPR correlations can be understood as challenging a strong version of ‘realism’ rather than the completeness of quantum mechanics or locality: in order for Bob to ascribe an element of reality to an event, he needs to be in causal contact with it. Through the wavefunction, Bob can predict what will be the outcome of the future communication (interaction) with Alice. However, he does not ascribe an element of reality to the outcome obtained by Alice’s measurement on the distant particle. It is by directly comparing these two distinct, spacelike separated contexts that the illusion of ‘non-locality’ (as a fundamental characteristic of the physical world) comes about.

What I intend to point out in the discussion of locality in relational quantum mechanics is that it appears that there is an implicit assumption in the way that the term ‘measurement’ is employed in relational quantum mechanics. It seems to be implicitly assumed that there is a difference between ‘direct’ and ‘indirect’ measurements: that is, when Bob makes a measurement on the other particle himself and when Alice communicates the result she obtained on her particle to him once they are back in causal contact. However, I argue that such a distinction is ill-posed and that measurements in quantum mechanics are always indirect measurements. I claim that if measurements in relational quantum mechanics are instead understood as indirect measurements, then physically meaningful events with respect to an observer need not be exclusively located within his past light cone. In the EPR case, Bob can ascribe an element of reality to the outcome obtained by Alice at the time she performed a measurement on her particle in a spacelike separated region from Bob’s, but this does not imply any violation of locality, nor does it depart from the RQM’s assumption that facts are sparse and relative because the causal chain that is reconstructed in a retrodictive way in order to ascribe an element of reality to the other particle’s outcome is nevertheless defined relative to a context of observation. (The expression ‘context of observation’ is borrowed from Grete Hermann. In section IV, I will make clear the relevance of Hermann’s ideas in the context of the present discussion). To articulate the claim, I will start by presenting Bohr’s reply to the EPR argument as recently analyzed by Guido Bacciagaluppi and Elise Crull, according to whom Bohr intended to minimize the difference between a measurement of one particle employing a single slit diaphragm and the EPR case (more precisely, Bohr understood these two cases as being perfectly analogous).[37]

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[37] G. Bacciagaluppi and E. Crull, ‘Bohr on EPR’, in: *The Einstein Paradox’: The Debate on Nonlocality and Incompleteness in 1935*, CUP), (forthcoming).

Section II – Bohr's Complementarity and the EPR Debate

2.1 Don Howard's Reconstruction of Bohr's Complementarity

In this subsection, I will present Bohr's view of complementarity following Howard's reconstruction. Howard speaks of a 'reconstruction' in the sense that it employs words and concepts that were not part of Bohr's writings. For instance, the reconstruction utilizes the term 'entanglement', a term not explicitly employed by Bohr. In fact, many scholars have argued that interest in the fundamental importance of quantum entanglement is a post-Bell phenomenon.[38]

Bohr's doctrine of complementarity has been (and sometimes still is) misunderstood mostly because of several physicists and philosophers (especially Heisenberg) that have claimed, as Don Howards maintains, to speak on Bohr's behalf to support their own philosophical agendas. Consequently, we have inherited decades of 'folklore' about Bohr's ideas. This 'folklore' understands the 'Copenhagen school' as a circle of thinkers that all shared the subjectivist interpretation of quantum mechanics which was proper of Heisenberg only.[39] In Howard's words:

> Everything not found in Bohr's complementarity interpretation is found in the writings of Heisenberg, and […] Heisenberg first introduced the term "Copenhagen interpretation" in 1955. Simply put, the image of a unitary Copenhagen interpretation is a post-war myth, invented by Heisenberg. But once invented, the myth took hold as other authors put it to use in the furtherance of their own agendas.[40]

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[38] D. Howard, 'Who Invented the "Copenhagen Interpretation"?', p. 672.

[39] For more literature concerning the Copenhagen Interpretation, I refer the reader to: J. Faye, 'Copenhagen Interpretation of Quantum Mechanics', *The Stanford Encyclopedia of Philosophy* (Winter 2019 Edition), Edward N. Zalta (ed.), URL = https://plato.stanford.edu/archives/win2019/entries/qm-copenhagen/

[40] D. Howard, 'Who Invented the "Copenhagen Interpretation"?', p. 675.

An important misconception that is proper of what Howard calls the ‘coincidence interpretation’ of Bohr is that he, like Heisenberg, treated the object under study quantum-mechanically in its entirety, while the agencies of measurement (e.g. a macroscopic measuring apparatus) are exclusively treated in classical terms and thus the quantum/classical distinction coincides with the instrument/object distinction.[41] Consequently, according to this ‘folklore,’ both Bohr and Heisenberg would have understood ‘measurements’ as special kinds of physical interactions, in the sense that they involve an interaction between two inherently different domains (the classical and the quantum) and therefore believed that subjectivism plays a central role in such interaction or, in more technical terms, that “[…] observation-induced wave packet collapse is a mode of dynamical evolution unique to measurement interactions.”[42] However, as Howard pointed out, this reading of Bohr is a misleading one: the basis of the doctrine of complementarity is quantum entanglement, not subjectivity or the collapse of the wavefunction.

According to Howard, Bohr takes ‘entanglement’ as the starting point for his doctrine of complementarity. More precisely, when we perform a measurement on a particle using a measuring apparatus, “the post-measurement joint state of the object plus measuring apparatus is entangled.”[43] To say that the states of the particle and the apparatus become entangled means that they form a non-separable whole, in the sense that we cannot ascribe an independent reality to each of them. However, this case does not allow for an objective description of the system: Howard argued that Bohr understood ‘unambiguous communicability’ to be the most important, necessary condition for objectivity.[44] ‘Unambiguous communicability’ is

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[41] D. Howard, ‘What Makes a Classical Concept Classical? Toward a Reconstruction of Niels Bohr's Philosophy of Physics’, p. 3. https://www.researchgate.net/profile/Don-Howard-2/publication/237526876_What_Makes_a_Classical_Concept_Classical_Toward_a_Reconstruction_of_Niels_Bohr's_Philosophy_of_Physics/links/0046353c6e3b70df9c000000/What-Makes-a-Classical-Concept-Classical-Toward-a-Reconstruction-of-Niels-Bohrs-Philosophy-of-Physics.pdf.

[42] D. Howard, ‘What Makes a Classical Concept Classical?’, p. 4.

[43] D. Howard, ‘Who Invented the “Copenhagen Interpretation”?’, p. 671.

[44] D. Howard, ‘What Makes a Classical Concept Classical?’, p. 8.

understood in a specific sense: to communicate in an unambiguous way what we have done in an experiment, one needs to be able to speak of the measured object as if the measured quantities were objectively 'possessed' by it. To do so, one needs to separate the state of the measured object from the state of the agencies of measurement and ascribe individual realities to them.

How does Bohr recover 'objectivity' and therefore 'unambiguous communicability' in light of these considerations? As Howard explains in his reconstruction of Bohr's doctrine, by the use of 'classical concepts' one can regain an objective description of the atomic phenomena under investigation because classical concepts embody the separability of the object of investigation and agencies of measurement. Howard argues that the doctrine of classical concepts plays a very important part in Bohr's thought because in embodying the separability between object and instrument, classical concepts allow us to 'unambiguously communicate' to each other the outcomes of our experiment. As such, the doctrine of classical concepts is a direct consequence of Bohr's notion of objectivity. As Howard puts it: "Classical physical concepts facilitate an unambiguous description, because, by assuming the separability of instrument and object, they enable us to say that *this definite object* possesses *this definite property*."[45]

Let me briefly explain the difference between classical concepts, which for Bohr need to be applied to an experimental situation in a complementary way to guarantee objectivity in the sense previously described, and the unintuitive formal symbols of quantum theory. I will explain the role of 'symbols' of the formalism of quantum mechanics following Dennis Dieks, who claims that Bohr was not an instrumentalist and that, despite the non-technical nature of

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[45] D. Howard, 'What Makes a Classical Concept Classical?', p. 11. (Emphasis in the original).

his writings, his thought was more connected to the formalism of quantum mechanics than one would expect.[46]

As Dieks explains, Bohr was a realist about entities such as electrons and photons and that the quantum formalism 'tells' something about them (according to Dieks, Bohr was not instrumentalist about quantum theory), namely that these entities are not to be thought of as we would in classical physics. Particles, according to quantum mechanics, cannot be described by values of variables such as energy, momentum, and position in the *same* way we would expect to do in classical mechanics: to simultaneously attribute sharp values to all such quantities would be inconsistent with the formalism of quantum theory because their applicability is restricted by the uncertainty relations. Therefore, familiar mathematical quantities (e.g. symbols such as p and q) do not refer to well-defined physical properties as we would expect them to in classical mechanics.[47] Quantum mechanics is 'symbolic' in the sense of "defying visualizability and literal interpretation."[48] To restore visualizability, the formal, 'symbolic' aspect of the theory has to make contact with physical reality: a mathematical scheme does not tell us anything about what the physical world is like. It can only do so when it is an interpreted physical theory.[49] To do so, one needs to employ 'classical' concepts and give a classical description of the experiment: a classical description "[…] is basically just the description in terms of everyday language, generalized by the addition of physics terminology, and it is the one we *de facto* use to describe our environment."[50]

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[46] It is important to note that Dieks, contrary to Howard who takes Bohr to be influenced by Kantian philosophy, claims that Bohr analyzed these issues in quantum mechanics from the perspective of a physicist rather than showing the typical attitude of a philosopher.

[47] D. Dieks, 'Niels Bohr and the Formalism of Quantum Mechanics', p. 5. https://www.researchgate.net/profile/Dennis-Dieks/publication/306228312_Niels_Bohr_and_the_Formalism_of_Quantum_Mechanics/links/57c752e008aefc4af34c7e4a/Niels-Bohr-and-the-Formalism-of-Quantum-Mechanics.pdf

[48] D. Dieks, 'Niels Bohr and the Formalism of Quantum Mechanics', p. 8.

[49] D. Dieks, 'Niels Bohr and the Formalism of Quantum Mechanics', p. 10.

[50] D. Dieks, 'Niels Bohr and the Formalism of Quantum Mechanics', p. 12.

Going back to Howard’s point, a description in terms of classical concepts allows us to *separate* the state of the object from the state of the measuring device and thus legitimates us to regard the object as truly ‘possessing’ the measured property, disregarding the fundamental quantum non-separability that characterize physical interactions in quantum mechanics. However, we cannot *unrestrictedly* apply such classical concepts, given that their application is limited by the uncertainty relations. Two physical quantities (like position and momentum) are said to be *complementary* if both are needed to determine the development of a physical system over time but they are mutually incompatible. To borrow words from Mauro Dorato, “[…] two properties are complementary if and only if they are *mutually exclusive* and *jointly* exhaustive.”[51] The reason is, according to Bohr, that doing so would require the simultaneous realization of two incompatible experimental arrangements. But relative to a certain experimental context where, for instance, we set up the device to measure the position of a particle, we can talk as if the particle itself *was* in a definite spatiotemporal location all the time: the application of the classical concept of *position* allows us to talk about the position of the particle and to make predictions about its future spatiotemporal locations but at the cost of its *momentum*, which becomes indefinite (and unpredictable) in this particular experimental arrangement. Let me explain this by means of the paradigmatic example of the slit experiment.

Let us suppose that the source emanates a beam of particles (the beam is reduced in such a way that only one particle is released at a time). We can set up the slit in two different ways, depending on which quantity we wish to measure on the particle. If, for instance, we intend to measure the position of the particle with respect to the apparatus when it passes through the slit, we need to fix the diaphragms *A*, *B*, and *C* to the rigid support: in this way, we can use diaphragm *A* to measure, in a fairly accurate way, the position of the particle when it collides with it. Here, we can regard the uncertainty in the particle’s position as due to the

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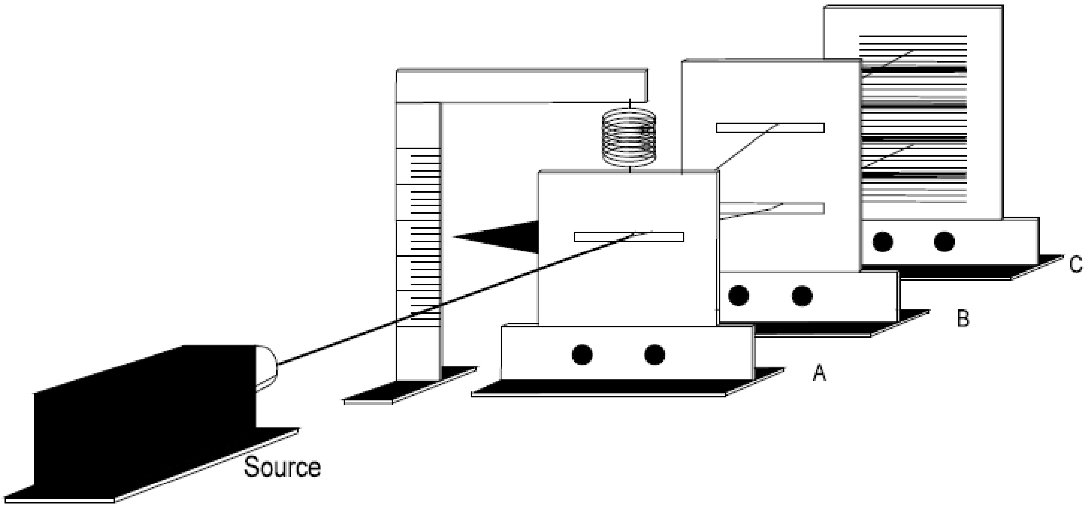
[51] M. Dorato, ‘Bohr meets Rovelli: a dispositionalist account of the quantum limits of knowledge.’ *Quantum Studies: Mathematics and Foundations* 7.2 (2020): 233-245, p. 240.

inaccuracy of our experimental device, since the uncertainty in the particle's position equals the width of the slit, but relative to such an experimental context this uncertainty does not amount to a fundamental one, it is merely due to the inaccuracy of our device and, at least in principle, it can be made more precise by narrowing the width of the slit. However, the uncertainty in the particle's momentum, relative to this experimental arrangement, is non-negligible in the sense that this experimental setup is not suited to measure the exchange of momentum, since it is imparted on the apparatus as a whole: measuring the momentum of the entire apparatus relative to some other system 'outside' of it would be of no practical use.

If, however, we set up the measuring apparatus in a different way, namely by 'releasing' diaphragm *A* from the common support, so that it can freely move in a given direction, then we can obtain a fairly accurate measurement of the particle's momentum (again, the uncertainty in momentum can be regarded as due to the limits of accuracy of our device and, in principle, we can *narrow* this uncertainty further and further by improving the device). If we measure the momentum of diaphragm *A* before the passage of the particle and subsequently we measure it again after the particle has passed through it, then we can apply the law of conservation of momentum and infer the particle's momentum during the passage. However, its position (crucially, both of the device and of the particle!) is completely indeterminate and again this indeterminacy *cannot* be regarded as due to imprecisions of the measuring device. These two experimental arrangements are mutually exclusive: it is not possible, in principle, to simultaneously realize both arrangements. Therefore, *position* and *momentum* are said to be complementary quantities because each of them can only be well-defined relative to a certain experimental arrangement that is not suited to measure the other quantity and both arrangements are not simultaneously realizable.



(Fig. 2.1: an illustration of Bohr's two-slit experiment).[52]

Crucially, complementarity does not imply that these limitations are merely epistemic. Rather, given that objectivity of atomic phenomena is recovered by the application of classical concepts that allow us to separate the state of the system from the state of the apparatus (which quantum mechanics would force us to regard as a unique, non-factorizable state) and that the application of classical concepts is limited depending on the particular experimental context that is realized in practice, it follows that the particle *has* a precise position and *no* definite momentum in an experimental context, while it *has* a definite momentum and *no* definite position in the other. In fact, Bohr preferred terms such as 'indeterminacy relations' rather than 'uncertainty relation' to emphasize the ontic aspect of these relations.

However, it is not only the particle that is treated quantum-mechanically in this measurement interaction. According to Howard, the crucial difference between Heisenberg and Bohr is that the former placed a cut between the object and the measuring device (which is freely movable either towards the microscopic object or the macroscopic apparatus) and treated one side of it entirely quantum-mechanically and the other side classically, while Bohr treated

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[52] D. Howard, 'What Makes a Classical Concept Classical?', p. 14.

certain aspects of both the device and the particle quantum-mechanically (the remaining aspects are treated classically).[53] Crucially, when we set up the measuring device to measure the position of the particle, we treat both the position of the diaphragm and of the particle classically, while the exchange of momentum between the particle *and* the diaphragm is treated quantum-mechanically and becomes completely uncertain: in other words, both the momentum of the particle and of the measuring device are subject to quantum mechanics. Therefore, the quantum/classical distinction in Bohr does not correspond to the microscopic/macroscopic distinction: the two descriptions 'cut across one another':

> What will be described classically are, by implication, only those properties of diaphragm *A* that are correlated with the observed system in the measurement. This means that, in the first arrangement, with fixed diaphragm *A*, the diaphragm's *position* would be described classically, since it is correlated with the photon's position, and in the second arrangement, with movable diaphragm *A*, the diaphragm's *momentum* would be described classically, because it is the property correlated with the photon's momentum.[54]

Let us now compare Bohr with Rovelli and clarify some further subtle aspects of Bohr's doctrine of complementarity.

2.2 Rovelli and the 'Coincidence Interpretation' of Bohr

In this subsection, I compare Howard's and Dieks' reconstruction of Bohr's doctrine with some of the key features of Rovelli's relational quantum mechanics. I claim that the way Rovelli characterizes Bohr's thought in his 1996 paper corresponds to the 'coincidence interpretation' described by Howard and therefore that he is mistaken in attributing to Bohr a commitment to

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[53] D. Howard, 'Who Invented the "Copenhagen Interpretation"?', pp. 674-675.

[54] D. Howard, 'What Makes a Classical Concept Classical?', p. 17

a quantum/classical dualism about reality. Let me report Rovelli's statement in question from his 1996 paper:

> Bohr assumes a classical world. In Bohr's view, this classical world is physically distinct from the microsystems described by quantum mechanics, and it is precisely the classical nature of the apparatus that gives measurement interactions a special status […] Bohr's choice is simply the assumption of a set of systems (the classical systems) as privileged observers. This is consistent with the view presented here. By taking Bohr's step, one becomes blind to the net of interrelations that are the foundation of the theory, and puzzled about the fact that the theory treats one system, S_0, the classical world, in a way which is different from the other systems. The disturbing aspect of Bohr's view is the inapplicability of quantum theory to macrophysics. This disturbing aspect vanishes, I believe, at the light of the discussion in this paper.[55]

As I have explained in section 2.1 following Howard, if one interprets Bohr as advocating an ontological distinction between microscopic and macroscopic reality, then one falls into what Howard has called 'the coincidence interpretation' of Bohr. There is thus no "disturbing aspect" in Bohr's view: neither Heisenberg nor Bohr intended that quantum theory is inapplicable to the macroscopic realm. It is true Heisenberg treated systems on one side of the cut quantum-mechanically while the systems belonging to the other side are treated entirely classically.[56] However, Heisenberg regarded the 'cut' as freely movable either in the direction of the object of measurement or towards the macroscopic apparatus. Importantly, as long as there is another system on the other side of the cut that is treated classically, nothing prevents us to apply quantum mechanics to the macroscopic apparatus as well, thus treating the interaction between the system and the measuring device quantum-mechanically.

Bohr as well was convinced that quantum mechanics is universally applicable. I have already explained in detail that Bohr treated classically parts of the measuring device and parts of the measured objects, specifically those quantities of both the system and the device that are

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[55] C. Rovelli, 'Relational Quantum Mechanics', p. 17.

[56] G. Bacciagaluppi, 'Better than Bohr: Grete Hermann and the Copenhagen Interpretation' (in preparation).

correlated by the measurement interaction, while the remaining aspects of the interaction are treated quantum-mechanically. Moreover, Dennis Dieks, who follows the 'rehabilitation program' of Bohr's views, has claimed that, since his earlier writings, Bohr argued that quantum theory is universally applicable, in the sense that it can in principle be applied to both microscopic and macroscopic systems.[57] Furthermore, the quantum-mechanical description is 'ontologically primary':

> This shows that Bohr considered it a matter of course that from an ontological point of view macroscopic objects are basically quantum-mechanical. […] The conclusion must be that for Bohr the necessity of using classical concepts has a purely *epistemic* status: it has to do with our access to the world, by means of macroscopic devices that are described by common language (extended by classical physics). It certainly does not correspond to any ontological dividing line between quantum and classical.[58]

Given this, I take Rovelli to refer to Heisenberg rather than to Bohr: it is true, in Heisenberg's account, that 'observers' have a sort of privileged classical status and that observations bring 'actuality' about (what Uffink and Hilgevoord have termed the 'measurement = creation' principle).[59] But Bohr, according to Howard, never endorsed such a view. Bohr never intended that 'observers' (in the sense of Heisenberg) play a crucial role in the measurement interaction. Bohr was careful in 'physicalizing' the observers and, instead of 'observers' he preferred locutions such as 'agencies of observation': the point is that Bohr did not regard 'measurements' as special sorts of interaction, special in the sense that they require conscious observers, or an interaction between two different sorts of physical systems, a quantum one and a classical one (this corresponds, rather, to Heisenberg's own view about measurements). A measurement, as any physical interaction, involves the two interacting systems being

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[57] D. Dieks, 'Niels Bohr and the Formalism of Quantum Mechanics', p. 14.
[58] D. Dieks, 'Niels Bohr and the Formalism of Quantum Mechanics', p. 16.
[59] J. Hilgevoord and J. Uffink, 'The Uncertainty Principle'. URL = https://plato.stanford.edu/archives/win2016/entries/qt-uncertainty/

‘entangled’, in the sense that they are not ‘separable’ (although he did not use the term ‘entanglement’ himself).[60]

I conclude this subsection by pointing out another interesting similarity between Bohr and Rovelli. As Dieks has claimed, it is not true that Bohr regarded the quantum state as an ontological entity and the ‘collapse’ of the wavefunction does not amount to a dynamical process, but it is merely a useful bookkeeping device to keep track of available information about measurement outcomes (which is very close to Rovelli’s view about the quantum state):

> One might get the impression that the interpretation of entangled states of object system plus a measuring device in terms of just one measurement result is a verbal move that is equivalent to accepting the projection postulate. If this were right, the interpretation would bring in the projection postulate via the back door, and would effectively violate what we have accepted as one of Bohr’s principles, namely that projection or collapse should not be seen as a dynamical evolution process, *but rather as a way of efficient bookkeeping that takes into account available information about experimental outcomes*.[61]

Therefore, I have pointed out that Rovelli’s understanding of Bohr’s doctrine coincides with the ‘coincidence interpretation’ because most of the ideas that he attributed to Bohr are in fact Heisenberg’s ideas. Rovelli’s view appears, on the contrary, to be quite close to Bohr as well. The measurement problem, understood as the problem of sorting out ‘measurements’ as special interactions between two different realities (a problem that Rovelli attributed to Bohr’s doctrine) that Rovelli claims to solve by regarding the world as entirely quantum-mechanical and thus by considering any physical interaction as a measurement, is, understood in this way, not a problem for Bohr because he was not committed to such an ontological dualism either: there are no two types of reality, one quantum-mechanical on the microscopic side of the cut and another inherently classical, therefore we cannot understand a measurement interaction as a ‘clash’ between inherently different realities. In conclusion, what Rovelli claims to be the

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[60] D. Howard, ‘Who Invented the “Copenhagen Interpretation”?’, p. 5.

[61] D. Dieks, ‘Niels Bohr and the Formalism of Quantum Mechanics’, p. 34 (Emphasis mine).

'disturbing aspect' of Bohr's doctrine appears to be an aspect of the 'coincidence interpretation' rather than a proper aspect of his doctrine of complementarity. It is entanglement, not subjectivism that characterizes measurement interactions (like any other kind of physical interaction) and is at the basis of the doctrine of complementarity.

In the next subsection, I will examine Bohr's reply to the EPR paper and the analogy between the single and double-slit experiments. I will then apply these insights to Rovelli's own treatment of the EPR correlations and I will use the insights that I will present in the next subsection, together with Hermann's account of the relative context of observation (to be introduced in section III) to claim that elements of reality, in RQM, can be retrospectively ascribed outside one's past light-cone.

2.3 The Analogy Between Single- and Double-Slit Experiments

As I have explained in section 2.1, Bohr's complementarity rests on the idea that certain quantities require the realization of mutually exclusive experimental arrangements in order to be measured with precision. Complementarity is not grounded in our epistemic limitation in defining such quantities in a precise way but, rather, it amounts to an ontic feature of the world: the particle *has no* simultaneously definite position and momentum. To recall Howard's analysis, it is only relative to a certain experimental context that we can speak as if the particle 'objectively' possesses a certain physical quantity (and, crucially, we gain the ability to make predictions concerning future values that such a physical quantity will assume upon further measurements).

To introduce the discussion about Bohr and his reply to EPR, it is important to point out that it is often claimed that, until 1935, the understanding of the doctrine of complementarity was grounded upon the idea that when we measure a physical quantity of a system we ‘mechanically disturb’ it: an ‘uncontrollable’ physical exchange takes place between the ‘agencies of observation’ and the system of interest that makes other quantities impossible to determine with precision (in an ontic rather than epistemic sense).[62]

Einstein, Podolsky, and Rosen (EPR for short) intended to criticize the idea that such a ‘mechanical disturbance’ determines which physical quantities of the object are definite (which of these quantities are ‘real’). Therefore, they elaborated a scenario involving two particles, prepared in a common state (the ‘singlet state’) and then measured at spacelike separated locations. EPR, in order to derive the conclusion in favor of the incompleteness of quantum mechanics, formulate the so-called ‘criterion of physical reality’:

> *If, without in any way disturbing a system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exists an element of reality corresponding to that physical quantity.*[63]

The conclusion of EPR is that, in short, there are elements of physical reality that are not included in the theory, and as such it is incomplete: if we carry out a measurement of position on one of the two spatially separated particles, we can infer the position of the other with certainty. But we may as well perform a measurement of momentum on one of the two particles and infer with certainty the momentum of the other, and in neither of these cases, we mechanically disturb one particle when measuring the other.

Therefore, the authors conclude that there are elements of reality that are not included in the theory, thus the theory is incomplete.

Bohr’s reply to EPR is one of the most discussed papers in the foundations of quantum mechanics and an important one for understanding Bohr’s complementarity. His reply is

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[62] A. Fine, ‘The Einstein-Podolsky-Rosen Argument in Quantum Theory’, *The Stanford Encyclopedia of Philosophy* (Summer 2020 Edition), Edward N. Zalta (ed.), URL = https://plato.stanford.edu/archives/sum2020/entries/qt-epr/.

[63] A. Einstein, B. Podolsky, and N. Rosen, ‘Can Quantum-Mechanical Description of Physical Reality be Considered Complete?’, *Physical review* 47.10 (1935): 777, p. 777 (Emphasis in the original).

concerned with undermining EPR's criterion of physical reality in quantum mechanics (while he has no problem in admitting its validity in classical mechanics):

> In fact, as we shall see, a criterion of reality like that proposed by [EPR] contains – however cautious its formulation may appear – an essential ambiguity when it is applied to the actual problems with which we are here concerned.[64]

Bohr disambiguated two different meanings of the sentence 'without disturbing a system' that figures in EPR's criterion of reality: the former is 'without mechanically disturbing a system', meaning without directly interacting with the system in question, therefore 'disturbing' it by a mechanical action; in the second sense, Bohr intends 'without disturbing a system' as 'without disturbing the conditions affecting the possibility of prediction on the system'.[65] It is this latter notion of 'disturbance' that EPR need to rule out to apply their criterion of reality. In Bohr's words, this 'non-mechanical' disturbance concerns "[…] *an influence on the very conditions which define the possible types of predictions regarding the future behaviour of the system.*"[66]

As Bacciagaluppi has pointed out, it is interesting to note that a very large part of Bohr's paper is concerned with the single-slit example, which had already been extensively discussed at the Solvay conference, while the novelty of EPR's argument involves two spatially separated particles. However, Bohr appeared to minimize the difference between the two cases, because he thought of them as being *strictly analogous*.[67] The reason is that the notion of 'non-mechanical' disturbance plays the very same role in both examples. Recall the example of the slit explained in section 2.1: we can realize two different, mutually exclusive experimental arrangements in order to measure either the position of the slit relative to the apparatus or the

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[64] N. Bohr, 'Can Quantum-Mechanical Description of Physical Reality be Considered Complete?', *Physical review* 48.8 (1935): 696, p. 697.

[65] G. Bacciagaluppi and E. Crull, 'Bohr on EPR', (forthcoming).

[66] N. Bohr, 'Can Quantum-Mechanical Description of Physical Reality be Considered Complete?', p. 700 (Emphasis in the original).

[67] G. Bacciagaluppi and E. Crull, 'Bohr on EPR', (forthcoming).

exchange of momentum that takes place between them upon collision. The crucial point is that in the experimental arrangement appropriate to measure the momentum of the particle (with the slit detached from the common support), we have two stages of the measurement procedure. The first stage of the measurement procedure involves a physical interaction between the particle and the measuring device (the passage of the particle through the slit). At this point, we still have the free choice to measure either the momentum or the initial position of the particle with respect to the rest of the measuring apparatus.[68]

The second step involves a later manipulation of the measuring device carried out by the experimenter: at this stage, we can freely choose to use the measuring device to measure the position of the particle in its *previous* interaction with the measuring apparatus, or to measure its momentum (which are two mutually exclusive, complementary arrangements!). Importantly, this second step takes place *after* the particle has collided with the measuring device. This is a crucial observation because it is in this sense that for Bohr there is "an influence on the very conditions which define the possible types of predictions regarding the future behaviour of the system."[69] If we wish to know the momentum of the particle, we can still do so after the particle and the measuring apparatus have interacted with each other, and depending on the further choice we make, we 'cut ourselves off' from the possibility of applying definite spatiotemporal coordinates to the particle (in an ontic, rather than epistemic sense). And this happens without there being any longer any mechanical disturbance between the apparatus and the particle. The same idea works if we wish to measure the position of one of the two particles (and consequently, of both of them).[70] In Bohr's words:

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[68] G. Bacciagaluppi and E. Crull, 'Bohr on EPR,' (forthcoming).

[69] N. Bohr, 'Can Quantum-Mechanical Description of Physical Reality be Considered Complete?', p. 700.

[70] G. Bacciagaluppi and E. Crull, 'Bohr on EPR', (forthcoming).

> […] we are therefore faced at this stage with a completely free choice whether we want to determine the one or the other of the latter quantities by a process which does not directly interfere with the particle concerned.[71]

It is such "non-mechanical disturbance" that makes the application of EPR's criterion of reality ambiguous in the case of quantum mechanics. Bohr argued that in order to make predictions on the future behavior of a system, not only do we need no mechanical disturbance of the system of interest, but it is equally crucial that we are able to reconstruct what happened during the previous interaction with the measuring device.[72] However, what we are able to reconstruct about the interaction depends on how we decide to use the device *after* the interaction has taken place.

This case of measurement is in perfect analogy with the EPR case. It becomes evident when we use another particle as measuring device for the former particle. The only difference between the single-slit experiment and the EPR case is that the interaction between the two particles is mediated by the double-slit diaphragm: a certain momentum was exchanged by the intermediary of the double-slit diaphragm. The latter plays no further role: if we measure the momentum of one particle, we can reconstruct the mediated exchange of momentum between the two particles, allowing us to carry out predictions regarding the momentum of the two particles after the interaction with the double-slit diaphragm.[73]

Let me summarize the insights presented in this subsection: according to Bohr, there is no difference between the following two cases: when we measure a certain quantity of a particle by means of a measuring apparatus (i.e., the slit) and when we *indirectly* measure it by making the particle collide with another and then measuring a certain quantity on the latter to predict with certainty the value of the corresponding quantity of the other (the EPR case). Therefore,

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[71] N. Bohr, 'Can Quantum-Mechanical Description of Physical Reality be Considered Complete?', p. 699.

[72] G. Bacciagaluppi, 'Did Bohr understand EPR?', p. 8.

[73] G. Bacciagaluppi and E. Crull, 'Bohr on EPR,' (forthcoming).

if in both cases we have this ‘non-mechanical disturbance’, then the two cases are perfectly analogous. In short, there is no difference between measuring a particle and realizing an EPR setup. All measurements are always *indirect* measurements because every measurement is an EPR case. There is no distinction between the two. This becomes even more evident when we compare the double-slit treatment of Bohr and the γ-ray microscope example discussed by Grete Hermann, where the collision between the photon and the probed electron realizes an EPR state, as Jammer pointed out to Weizsäcker in 1967.[74] In the next section, I introduce Grete Hermann’s ideas on the relative character of quantum-mechanical description and her account of retrospective causality. The γ-ray example and its analogy with Bohr’s treatment of the single-slit experiment will be discussed in section 3.2.

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[74] G. Bacciagaluppi, ‘Better than Bohr’, (in preparation).

Section III: Grete Hermann's Retrospective Causality and a Comparison with Rovelli's Relational Interpretation

In this section, I introduce Grete Hermann's ideas about the relative character of quantum-mechanical description and her view about the notion of causality in quantum mechanics. After a brief introduction to Hermann's philosophical views on quantum theory, I will present her analysis of the γ-ray microscope in section 3.2, where she employed a selective use of classical concepts that has analogies with Bohr's discussion of the slit experiment, especially in light of Don Howard's reconstruction of Bohr's doctrine of classical concepts.[75] Furthermore, I will show in section 3.3 that many important ideas that characterize Hermann's views about quantum theory can be compared with Rovelli's relational interpretation of quantum mechanics. In comparing Rovelli's relational interpretation with Hermann's ideas, I intend to show that Hermann's account of retrospective causality nicely fits in Rovelli's interpretation and can even enrich his characterization of causality, specifically the idea in relational quantum mechanics that the correlations between particles in an EPR scenario can be accounted for by means of a common cause in an indeterministic context.

3.1 Hermann's Context of Observation and Retrospective Causality

Let me start by giving an introduction to Hermann's philosophical background. A first important point to note is that Hermann was convinced that the Kantian transcendental philosophy (more specifically, Fries' interpretation of Kant) was the best framework to articulate ethical and epistemological issues of her times.[76] Hermann's main worry centred on

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[75] G. Bacciagaluppi, 'Bohr's slit and Hermann's Microscope.' *Grete Hermann-Between Physics and Philosophy*. Springer, Dordrecht, (2016). 135-147, p. 139

[76] L. Soler (2016) 'The Convergence of Transcendental Philosophy and Quantum Physics: Grete Henry-Hermann's 1935 Pioneering Proposal'. In: Crull E., Bacciagaluppi G. (eds) *Grete Hermann* -

claims according to which quantum theory refutes the validity of the Kantian category of causality. As nicely explained by Léna Soler, while Kant listed the conditions of possibility of knowledge that any future science must be based on (in particular, the category of causality, namely a one-to-one correspondence between causes and their effects), quantum physics seemed to refute the Kantian category of causality, especially in light of the limitations on prediction imposed by the uncertainty relations.[77]

The problem is that the Kantian notion of causality (as a one-to-one correspondence between causes and their effects) is tied to the possibility of predicting with certainty the physical state of a system at any instant of time, given the complete knowledge of all causes, whereas predictions of quantum mechanics are essentially statistical. At first, Hermann was not convinced about the completeness of quantum mechanics and criticized Von Neumann's proof on the impossibility of completing quantum theory through additional variables (interestingly, anticipating Bell's later criticism of Von Neumann's proof).[78] Supplementing the theory with additional variables may restore its determinism and thereby maintaining a Kantian understanding of causality. However, she did not pursue the path of hidden variables but changed strategy by maintaining that it is pointless to supplement quantum theory with additional variables because she argued that quantum mechanics is already a causally complete theory.

The crucial point of Hermann's thought that led her to accept the completeness of quantum theory is that quantum-mechanical descriptions of a physical event do not belong or refer to the physical system 'by itself' but they are always relative to an observational context. As Soler nicely put it, the core of Hermann's interpretation is the following:

Between Physics and Philosophy. Studies in History and Philosophy of Science, vol 42. Springer, Dordrecht, p. 55.

[77] L. Soler, 'The Convergence of Transcendental Philosophy and Quantum Physics', p. 58.

[78] L. Soler, 'The Convergence of Transcendental Philosophy and Quantum Physics', p. 61.

> The results of measurements actually obtained for quantum objects cannot be univocally predicted with certainty. However, *after* having performed a quantum measurement, and *after* having gained knowledge of its result (previously not predictable with certainty), it is possible, by working backwards, to reconstitute, retrospectively and completely, the causal chain which has necessarily produced such a result.[79]

The essential idea is that causality should not be understood as a concept concerned with the objective (context-independent) course of physical events: predictions only become possible when we apply classical concepts to describe a phenomenon and this can be done in a complementary way, depending on the context of observation one enters. Thus, for Hermann, the most important lesson of quantum mechanics concerning the notion of causality is that we must separate the principle of causality in itself (which states that every natural phenomenon is always caused by a preceding event) from the assumption that "[…] physical knowledge accounts for natural events *adequately and independently of the observational context*."[80]

What Hermann intended to argue is that the statistical character of quantum mechanics does not refute the Kantian category of causality: prediction and causality are two different principles that are often (and wrongly) lumped together and quantum mechanics teaches us that these two principles must be separated from each other.

This leads us to what Elise Crull has called Hermann's most important insight: the idea that quantum-mechanical descriptions of nature are never 'absolute' but always relative to a context of observation. Crull argued that Hermann's 1935 essay has not been written with the premeditated end to retain the validity category of causality in quantum mechanics and that the relativity of quantum-mechanical descriptions merely follows from her considerations about causality. Quite the contrary: the solution to the question of the causal completeness of quantum

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[79] L. Soler, 'The Convergence of Transcendental Philosophy and Quantum Physics', p. 63.

[80] G. Hermann 'Natural-Philosophical Foundations of Quantum Mechanics'. In: Crull E., Bacciagaluppi G. (eds) *Grete Hermann - Between Physics and Philosophy*. Studies in History and Philosophy of Science, vol 42. Springer, Dordrecht (2016), 239-278, p. 264 (emphasis mine).

mechanics is not retrodictive causation, but the realization that quantum-mechanical descriptions of nature are relative to a context of observation.[81]

To understand in which sense quantum mechanics is causally complete relative to a context of observation it is important to characterize Hermann's use of classical concepts, which interestingly is analogous to Bohr's under the light of Howard's reconstruction.

Specifically, Hermann maintained that there are three levels of descriptions in which complementarity plays a role (the last one being the most fundamental sense in which she understands complementarity): (i) complementarity between the classical wave and particle pictures (that is the wave or corpuscular interpretation of a quantum object); (ii) complementarity between specific quantities in each of these pictures (for instance, position or momentum in the corpuscular picture); (iii) most importantly, complementarity between the 'unintuitive' quantum-mechanical description (which employs wave functions in abstract space, which are not visualizable as, for example, the classical description we would give of the motion of an object) and the intuitive classical descriptions that enable us to connect quantum mechanics to our experience.[82]

As pointed out by Crull, the deep reason for complementarity is, in Hermann's view, the relative character of quantum-mechanical descriptions. The reason is that classical pictures, which form the bridge between quantum mechanics and our experiences, are applicable only within the limits imposed by the uncertainty relation. However, within these limits, they allow us to 'understand' (in the Kantian sense of applying transcendental categories to account for experience) the phenomena and to identify its causes, allowing precise predictions of the outcome of future measurements.[83] However, deterministic predictions are no longer possible

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[81] E. Crull 'Hermann and the Relative Context of Observation'. In: Crull E., Bacciagaluppi G. (eds*)* *Grete Hermann - Between Physics and Philosophy*. Studies in History and Philosophy of Science, vol 42. Springer, Dordrecht (2016), 149-169 p. 163.

[82] G. Bacciagaluppi, 'Better than Bohr', (in preparation).

[83] E. Crull, 'Hermann and the Relative Context of Observation', p. 168.

when one changes the context of observation: one cannot use the causes of an event that we retrospectively find in a certain observational context to make predictions concerning measurements in different observational contexts. Descriptions belonging to different contexts can only be related statistically. An example is measuring either the position of a particle or the momentum: the particular experimental set-up that we choose in order to measure either the particle or the position of a particle will determine the context of observation one enters relatively to which particular descriptions of the object become possible. Moreover, according to Hermann one is always in the position to retrospectively find the causes of a given experimental outcome.

To understand Hermann's use of the classical pictures and its analogy to Bohr, let us consider the γ-ray microscope experiment as analyzed by Grete Hermann, which will be the topic of the next subsection.

3.2 Hermann's Treatment of the γ-Ray Microscope

In analyzing the microscope experiment, Hermann discusses von Weizsäcker's treatment and uses his results to argue that quantum mechanics is already a causally complete theory.[84] Imagine an electron that moves freely within a given plane of the γ-ray microscope. The momentum of the electron is known but its precise location within the plane is uncertain. We then illuminate it with a photon of known momentum. Depending on whether we wish to measure the electron's position or momentum, we place the photographic plate (on which we record the scattered photon) either in the image plane of the microscope or in the focal plane.

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[84] T. Filk, 'Carl Friedrich von Weizsäcker's 'ortsbestimmung eines elektrons' and its influence on Grete Hermann.' *Grete Hermann-Between Physics and Philosophy*. Springer, Dordrecht, (2016), 71-83, p. 73.

In Hermann’s words, depending on the placement of the photographic plate, one enters in a certain observational context in which certain (classical) descriptions become possible.

In the first case, already described by Von Weizsäcker, we place the photographic plate in the image plane of the microscope to measure the precise position of the electron. The interaction between the electron and the photon is interpreted as a corpuscular collision: in this case, we are working with the classical conception of ‘corpuscle’ and we imagine the electron and the photon as two small particles colliding at a single point in space within the microscope. Immediately after the collision, the motion of the scattered photon is instead described not as the classical motion of a corpuscle but through the wave picture: immediately after the collision, the motion of the photon is described as a spherical wave emanating from the point of the (corpuscular) interpreted collision, reaches the lenses of the microscope and is redirected towards a single point on the photographic plate, darkening that particular spot. Depending on the darkened spot on the photographic plate, we are able to calculate the centre of the spherical wave, which corresponds to the precise location of the collision between the electron and the photon, thus to the position of the photon at the time of the collision.[85]

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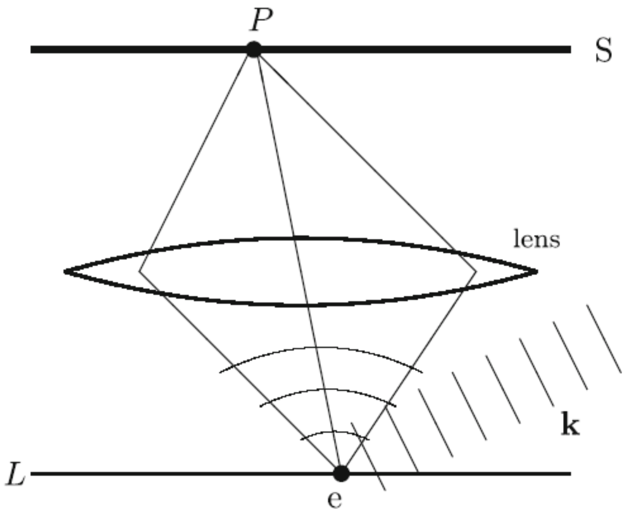
[85] T. Filk, ‘Carl Friedrich von Weizsäcker’s ‘ortsbestimmung eines elektrons’ and its influence on Grete Hermann’, p. 73.



(Fig. 3.1: representation of the collision between the photon and the electron in the γ-ray microscope, with the photographic plate placed in the image plane).[86]

In the second case, with the photographic plate placed in the focal plane of the microscope, the analysis is different. The motion of the scattered photon is described, in this case, not as a spherical wave but as a planar wave. This particular kind of picture allows us, depending on the darkened spot on the photographic plate, to calculate the exact exchange of momentum between the electron and the photon at the time of their collision, and therefore the momentum of the electron.[87] However, the exact location of the collision is unknown. In Hermann's terminology, we can think, relative to this latter observational context, that there was a definite exchange of momentum but that the (corpuscular interpreted collision) took place in no definite spatial location in the microscope.

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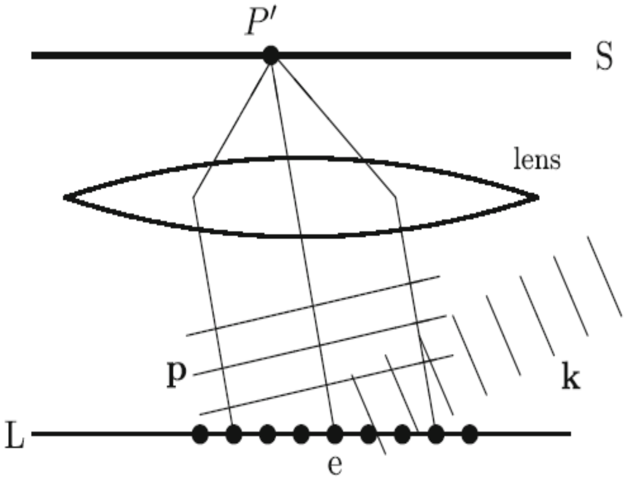
[86] T. Filk, 'Carl Friedrich von Weizsäcker's 'ortsbestimmung eines elektrons' and its influence on Grete Hermann', p. 74.

[87] T. Filk, 'Carl Friedrich von Weizsäcker's 'ortsbestimmung eines elektrons' and its influence on Grete Hermann', pp. 74-75.



(Fig. 3.2: the microscope experiment with the photographic plate placed in the focal plane).[88]

In addition to these two cases, already present in Von Weizsäcker's treatment of the microscope which Hermann addresses, her analysis includes a third interesting case: the photographic plate is placed nowhere at all. In this case, we have another, 'unintuitive' description of the collision (which corresponds to entanglement) because we lack a context of observation relative to which the electron and the photon possess definite momentum or position and therefore there is no classical analysis possible:

> Finally, if one sets up no photographic plate at all, but allows the light quantum to pursue its path without detecting it, then one obtains yet a third – though not in the same way intuitive – description of the state after the collision. In this case, the physical system composed of the light quantum and the electron is assigned a wavefunction that describes a linear combination: each of its terms is the product of one wave function describing the electron and one describing the light quantum. Through this linear combination the light quantum and the electron are thus not described each by itself, but only in their relation to each other. Each state of one is associated with one of the other.[89]

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[88] T. Filk, 'Carl Friedrich von Weizsäcker's 'ortsbestimmung eines elektrons' and its influence on Grete Hermann', p. 74.

[89] G. Hermann, 'Natural-Philosophical Foundations of Quantum Mechanics', p. 258.

The analogy between Hermann's and Bohr's selective use of classical concepts becomes evident when we read Bohr's complementarity through Howard's reconstruction. Howard argued that Bohr selectively applied classical concepts to both the system of interest and the apparatus instead of treating the former exclusively quantum-mechanically and the latter exclusively classical. Howard's reconstruction of Bohr equally fits Hermann's treatment of the γ-ray microscope.[90] Hermann provided retrospective causal analyses by selectively applying classical concepts depending on the particular observational context one enters by placing the photographic plate either in the image or in the focal plane. Furthermore, recall that according to Howard, quantum entanglement constituted the basis of Bohr's complementarity, according to which two systems cannot be regarded as two separate entities when they are entangled. Hermann's third scenario (in which no photographic plate has been placed at all) is formalized in terms of entanglement, in the sense that there is no context of observation relative to which we can apply classical concepts that allow us to regard the particles as possessing certain definite properties (to compare with Bohr: there is no experimental context relative to which 'objectivity' can be regained).

The point is that under the light of Howard's reconstruction, Bohr's discussion of the double-slit experiment in his reply to EPR is analogous to Hermann's treatment of the γ-ray microscope. In fact, it was already pointed out by Max Jammer to von Weizsäcker that the γ-ray microscope realizes an EPR scenario: the electron and the particle become entangled upon interaction and by measuring the one, we measure the other as well.[91]

In discussing the analogy between these two experiments from Bohr and Hermann, I intended to show that all measurements in quantum mechanics should be understood not as direct measurement (as Rovelli implies by considering measurements as any physical interaction between any physical systems), but rather as indirect measurement. Measurements

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[90] G. Bacciagaluppi, 'Bohr's Slit and Hermann's Microscope', p. 140.

[91] G. Bacciagaluppi, 'Better than Bohr', (in preparation).

are always indirect in the sense that they require two physical interactions: one between the system of interest and an auxiliary system (as I have shown in the case of Bohr's double-slit experiment and Hermann's γ-ray microscope, it does not matter if the role as the auxiliary system is assumed by a particle or a macroscopic measuring device) and one further interaction between the auxiliary system and the experimenter, which takes place at a later time when the system of interest is no longer involved in physical interaction with the auxiliary system.

To understand this, let us formulate the following general example of indirect measurement, borrowing Rovelli's terminology of 'relative fact'. In the first stage of measurement, there is a physical interaction between the system of interest (the particle) and the auxiliary system (let us consider it as a macroscopic device for simplicity). In Rovelli's terms, a relative fact is established between the particle and the device that measure its spin: the particle has a definite spin relative to its interaction with the measuring device. In the second stage, a relative fact is established between the measuring device and the experimenter that manipulates it: we can say that the outcome 'spin up' has been displayed by the measuring device relative to the experimenter. However, if a physical event happens only at the time of an interaction, in the sense that two physical systems possess definite properties only at the time of their interaction (when they 'measure' each other), then there is no more relative fact happening between the particle and the device at the time the experimenter interacts with the latter. As I will discuss in the final section, if measurements are direct then the experimenter can regard as physically real only the outcome displayed by the measuring device with respect to themselves, but it is unclear how the experimenter can regard the previous interaction between the particle and the device as physically real. That is, it is unclear how the experimenter can account for the particle 'being spin up' at the time of its measurement (in the first stage in this case): only the outcome displayed by the device has physical reality relative to the experimenter.

I argue that if measurements are understood rather as indirect measurements, then the experimenter can regard the particle as having a certain property at the time of its interaction with the device. I claim this by borrowing Grete Hermann's insight about retrospective causation that I have discussed in the preceding sub-section: by retrospectively applying a causal analysis starting from the outcome obtained (the second stage) to the particle being 'spin up' in the first stage, the experimenter is able to ascribe an element of reality to the property of the particle itself.

In the coming sub-section, I put Hermann's and Rovelli's accounts in comparison in order to show why I think that Hermann's account of retrospective causation can fit Rovelli's discussion of causality and locality in his relational interpretation of quantum mechanics.

3.3 Hermann in Comparison to Rovelli

Here, I argue that the analysis of Grete Hermann's insights presented in the previous sub-section can also be applied to Rovelli's account. In fact, I argue that Hermann's views about the relative context of observation can be put in analogy with Rovelli's claim that physical descriptions of systems are complete descriptions relative to a context of interaction. More precisely, I aim to show that Rovelli's treatment of the EPR correlations, in which he invokes a notion of 'common cause' (though rejecting a classical characterization of it) to give a local account of them, can be enriched by Hermann's characterization of (retrospective) causality which, as pointed out by Elise Crull, is ultimately rooted in her recognition of the importance of the relative character of quantum-mechanical descriptions.[92] However, the consequence arising from the present considerations concerning relational quantum mechanics is that "elements of reality" need not necessarily be meaningfully ascribed, from the perspective of an observer, solely to those systems with which it 'directly' interacted in his past: if Rovelli

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[92] E. Crull, 'Hermann and the Relative Context of Observation', p. 174.

insists that elements of reality are ascribed at the time of the interaction between particles, then such elements of reality are ascribed by the observer to past events (since such an interaction takes place within the observer's past light-cone). What I intend to claim is that elements of reality can also be ascribed to another system that previously interacted with the physical system (a measuring device or another particle used as an 'ancilla') that the experimenter then manipulates to measure the former, regardless of whether the former system is still located within the observer's past light-cone or not.

I will now highlight what I think are the relevant similarities, in order to show why this conclusion follows. I claim that the points in common are the following:

1. They both agree, in similar ways, that quantum-mechanical descriptions of a physical event are complete descriptions relative to the perspective of an observer (or a context of observation);
2. They both insist on the idea that descriptions of events belonging to different contexts of interaction cannot be directly compared;
3. Outcomes of measurements are causally determined (in the sense that they are caused by a preceding event), but causes cannot be used to predict with certainty the course of future events.

The first comparison I wish to highlight is that both Rovelli and Hermann have insisted that quantum-mechanical descriptions of a physical event are complete relative to a context of observation. Rovelli does not use the term 'context of observation', which is a term that we find in Hermann's writings. He prefers speaking about 'observers', although they have no intrinsic classical character. However, I do not see a difference in the way such notions are put to use by the respective authors, even if the analogy might not be as obvious: we can conceive a 'context of observation' in the relational interpretation as a context of interaction, realized between the systems in question, and to which we relativize the description we give of those systems. Hermann herself emphasized that a context of observation is brought about by the interaction between the measured object and the measuring instrument. She appears to claim that it is indeed the interaction that matters in bringing about a context of observation: the role of the observer is just that of choosing a particular interaction rather than another (to interact with the slit in a certain way in order to bring about the physical interaction with the slit needed to ‘measure’ the momentum of the particle rather than its position, for example), which makes her position rather analogous to that of Rovelli:

> The process of measurement, through the interaction between object and measuring instrument, creates a new context of physical observation, in which both systems are presented to the observer in a new way that cannot be uniquely predicted from the previous one.[93]

Hermann’s point is that given a context of observation, brought about by the physical interaction between the particle and the device, we can causally explain how a particular outcome was obtained, but the knowledge of such causes does not enable one to predict with certainty the outcomes of future interactions between the objects in question. To do so, one would need to account for causal events from a context-independent perspective and Hermann firmly believed that quantum mechanics provides a complete description of events *relative* to a context of observation, that is, relative to the kind of physical interaction that took place between them. We can further see that Rovelli insists precisely on the impossibility of accounting for physical facts from an absolute ‘point of view’, given that quantum mechanics is a complete theory about relative facts, which is in fact what also Hermann recognized in her 1935 essay. Rovelli writes:

> *Quantum mechanics is a theory about the physical description of physical systems relative to other systems, and this is a complete description of the world.* […] Thus, I propose the idea that quantum mechanics indicates that the notion of a universal

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[93] G. Hermann, ‘Natural-Philosophical Foundations of Quantum Mechanics’, p. 256.

> description of the state of the world, shared by all observers, is a concept which is physically untenable, on experimental grounds.[94]

The idea that quantum mechanics describes particles as possessing ‘objective’ properties independently of any observational context was also similarly dismissed by Hermann:

> Despite all the failures of the classical theories, quantum mechanics also retains the method of proceeding from observation to the explanation of nature through the construction of such models and of he causal regularities valid within them. Forced by contrary experiences, it has only broken with the single assumption that these models describe the course of nature *objectively*, that is, independently of the observer and the manner in which he observes.[95]

Furthermore, the reason why Hermann came to believe that quantum mechanics is a complete theory (in the sense that the completion of it by means of hidden variables would lead to overdetermination) is also grounded in her insight that descriptions of nature are always relative to a context of observation:

> Rather, the quantum-mechanical formalism itself already contains the reasons that rule out such a completion. Control of the arising disturbance does not fail because the formalism is still defective with respect to the explanation of this disturbance and thus in need of completion but because the explanations it provides – which are complete and therefore not liable to emendation – are valid, as are all quantum-mechanical statements, only relative to a certain observational context.[96]

This is another view that Rovelli has in common with Hermann, in that he insists upon the complete description of nature provided by quantum mechanics relative to the context of observation that an observer enters when performing a measurement and that such a description does not allow one to predict with certainty the outcome of future interactions between it and other systems.

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[94] C. Rovelli, ‘Relational Quantum Mechanics’, p. 7.

[95] G. Hermann, ‘Natural-Philosophical Foundations of Quantum Mechanics’, p. 269.

[96] G. Hermann, ‘Natural-Philosophical Foundations of Quantum Mechanics’, p. 260.

As for the second point of comparison, both Hermann and Rovelli insist that descriptions relative to different contexts cannot be directly compared. In the EPR case, Rovelli insists that when Alice and Bob make a measurement on their respective particles in spacelike separated regions, Bob cannot account for events taking place at Alice's location and vice-versa: they can only compare results once they are back in causal contact. Similarly, Hermann argued that it is pointless to ask what would have happened in a different context of observation other than the one we find ourselves in. What we can say about the EPR scenario relying on Hermann's account of the relative context of observation, is that the respective measurements carried out by Alice and Bob belong to different contexts and they cannot be directly compared. Once Bob and Alice meet each other again, they enter in a new context of interaction relative to which comparison becomes possible because the causes that brought about the outcomes are now present in this new context (which can be retrospectively checked) and cannot have been part of the old one. This brings us to another important point of comparison concerning causality and the EPR scenario: as I mentioned at the beginning of this section, I believe that Hermann's considerations about the retrospective character of causality make sense in causally accounting for the EPR correlations within the framework of the relational interpretation since Rovelli believes that there can be a local, causal explanation of them that fits together with indeterminism in the same conceptual framework.[97] Hermann's considerations fit well with such a scenario.

In 'The Notion of Locality in Relational Quantum Mechanics', the authors make the following remark about causality in the EPR scenario: "Since A and B are space-like separated, a classical observer O observing correlations between past events A and B would be lead to the conclusion that there is a common cause to A and B."[98] Their idea is that since there is no

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[97] P. Martin-Dussaud, C. Rovelli and F. Zalamea, 'The Notion of Locality in Relational Quantum Mechanics', p. 5.

[98] P. Martin-Dussaud, C. Rovelli and F. Zalamea, 'The Notion of Locality in Relational Quantum Mechanics', p. 4.

‘action at a distance’ between Bob’s and Alice’s measurement, then their respective outcomes had to be determined by a causal succession of events, but this causal story can be checked only from an observer lying in a common region of the future light-cones of Alice and Bob. Therefore, the authors argue that from the perspective of such a future observer, the outcomes of their measurements appear correlated not because there is superluminal causal influence between them, but because there must be a common cause that explains the correlations between the particles. However, the authors insist that having complete knowledge of the relevant causes does not entail determinism and does not give a precise characterization of the notion of common cause here involved, referring to it as an ‘intuitive’ notion of ‘common cause’. In their words:

> In the classical case, the notion of causation is strongly related to that of determinism, hence the idea that a complete knowledge of the past would entail a complete knowledge of the future. In quantum mechanics, there is no such a determinism. […] Nevertheless, the intuitive notion of causation does not disappear from the quantum world: in our example it is still meaningful to say that the radioactive element is the ‘common cause’ of the correlations observed later, even if one cannot predict from the past knowledge whether the α particle will be observed in A or in B. To be clear, we are here referring to an intuitive notion of ‘common cause’ and not to the formal notion introduced by Reichenbach. […] In fact, ‘non-locality’ exemplifies the difficulty to understand together ‘causality’ and ‘indeterminism’ in the same conceptual and mathematical framework.[99]

The authors mention that the problem of non-locality reduces to the difficulty of merging causality (which is usually understood in a deterministic sense, so that a complete knowledge of the causes entails a complete knowledge of their future effects, which Rovelli rejects) with the indeterministic character of quantum theory: he rejects a deterministic notion of causation, but he does not really tell us what place causality occupies in an indeterministic framework. However, Grete Hermann’s account of retrodictive causality, I argue, can be also understood

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[99] P. Martin-Dussaud, C. Rovelli and F. Zalamea, ‘The Notion of Locality in Relational Quantum Mechanics’, p. 5.

in the framework of relational quantum mechanics and could make sense of the notion of causality in treating the EPR pairs within such a framework. The reason why I believe so lies precisely in her idea that quantum-mechanical descriptions of events are causally complete relative to a given context of observation: that quantum-mechanical descriptions of events are complete (though not context-independent) is also the core idea of Rovelli's relational interpretation.

Hermann's insight that interests us here is her claim that quantum mechanics, given that the descriptions it provides are complete relative to a context of observation, forces one to disentangle the principle of causality in itself from the criteria of its application. In her essay of 1935, Hermann explained that the uncertainty relations set an unsurmountable limit to the accuracy of the predictions that we can jointly carry out and argued that this is clearly in contrast with the idea that a complete knowledge of causes would entail a complete knowledge of future development of every natural event:

> And yet this idea was only the expression of the certain conviction that every natural event in all its features has been caused by preceding events, and thus must be predictable from these causes for one knowledgeable of the natural laws. Together with the faith in the unlimited possibility of such predictions, also the conviction in the pervasive causal connection of natural events thus come to falter.[100]

As explained in the previous section of this essay, Hermann's insight was to recognize that different principles are clumped together into this idea of causality and that they should be distinguished: on the one hand, the principle of causality itself is preserved and it is not true that there are acausal processes (or faster-than-light processes) in nature; on the other, its criteria of application are limited by the uncertainty relations, so that it is not possible to carry out predictions with unlimited precision about, for instance, the future motion of a particle at

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[100] G. Hermann, 'Natural-Philosophical Foundations of Quantum Mechanics', pp. 241-242.

every single instant of time, which is in fact determined by its instantaneous position and momentum at any instant, and these are not measurable simultaneously due to the limit set by the uncertainty relations.[101] In Hermann's words:

> Seen in this light, the difficulties into which the advocate of the law of causation is plunged by the discoveries of quantum mechanics are rooted in the fact that various principles have been merged together: the principle of causality in the narrower sense whereby every event in nature has causes from which it follows with necessity, has been merged with the assumption that physical knowledge accounts for natural events adequately and independently of the observational context. […] Quantum mechanics requires us to resolve this merging of different natural-philosophical principles – to drop the assumption of the absolute character of the knowledge of nature and to handle the principle of causality independently of it. Consequently, it has not refuted the law of causality, but has clarified it and freed it from other principles that are not necessarily connected with it.[102]

Thus, we can see that Rovelli shares a similar worry as Hermann with respect to causality in an indeterministic framework. I wish to note that Rovelli explicitly insists on maintaining a notion of common cause to save the principle of "no superluminal causal influence".[103] Hermann, on the other hand, did not arrive at her conclusion on causality starting from considerations about locality but saw the solution concerning causality in the relative character of quantum-mechanical descriptions, a basis that both Rovelli and Hermann share and from which they built up their respective ideas about the foundations of quantum mechanics. What happens is that, in order to explain the individual results, Alice and Bob need to invoke two separate and incompatible descriptions of the previous interaction between their two particles. When they get together and want to explain the correlations, they need to invoke not the interaction between their two particles, but their previous interactions with their own particles.

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[101] G. Hermann, 'Natural-Philosophical Foundations of Quantum Mechanics', p. 246.

[102] G. Hermann, 'Natural-Philosophical Foundations of Quantum Mechanics', p. 264.

[103] P. Martin-Dussaud, C. Rovelli and F. Zalamea, *'The Notion of Locality in Relational Quantum Mechanics'*, p. 1.

Another important point in common is that both Rovelli and Hermann consider interactions (or contexts of interaction) at specific times. In the case of Hermann's treatment of the γ-ray microscope, a particular context of observation comes about at the time the scattered photon interacts with the photographic plate and, depending on where one had placed the plate, the relative description we give of it will contain some aspects (the classical concept that we can apply) of the original collision between the photon and the electron, depending on the subsequent kind of interaction between the photon and the photographic plate. Rovelli considers properties of physical systems as actualized upon their interaction: since properties are relational, they express how a given system physically influences a second system, given the context of their interaction.

I will now rely on the preceding analysis to explicate the claim that elements of reality ascribed to a particle (by retrospectively checking its causal past) are maintained even after the particle no longer interacts with the physical system (macroscopic or microscopic) used as a measuring device. According to Rovelli's relational interpretation, properties are assumed by systems solely upon the time of their interaction: once these systems stop interacting, they stop having 'actual' properties. What we are left with after the interaction is a 'quantum state' in the hands of the physicists that they may use to predict what values the variables of a given system will assume upon future interactions with other systems. However, in a recent paper titled *Stable Facts*, Rovelli and Di Biagio talk about 'stable facts', that is, relative facts that become independent of the particular systems relative to which they are defined. I claim that also the notion of 'stable facts' in Rovelli's relational interpretation can be formulated in terms of causation, in the sense that when we retrospectively construct the causal link between the interaction between two systems, say A and B, and a later interaction of A or B with a third system C, that we consider the elements of reality pertaining to A to be independent of whether we consider them relative to B or C.

If we implement Hermann's views about the retrospective character of causality and the relative context of observation, then we can argue that the physicists can still ascribe an element of reality to the particle they wish to measure after the interaction with their measuring device took place and, in fact, they do so retrospectively by manipulating the measuring device in a proper way to measure some appropriate quantities of the particle in question, and successively ascribing elements of reality to those quantities. This is in fact what happens in every measurement: elements of reality to particles are always applied retrospectively, after the interaction between the particle and the measuring device has taken place, by appropriately manipulating the measuring device and by further reconstructing the relevant causal succession of events that has brought about a particular reading of the apparatus. In the next section, I will conclude the thesis by showing how the insights developed so far can be applied to reformulate the EPR scenario in relational quantum mechanics, showing that given such insights the EPR correlations can be locally accounted for within the framework of the relational interpretation.

Section IV – Elements of Reality in Relational Quantum Mechanics

4.1 Should Elements of Reality be Confined Within an Observer's Past Light-Cone?

In this section, I articulate my claim that, in the relational treatment of the EPR correlations, Alice and Bob can regard each other's particle's spin as a beable relative to the context of observation they enter by measuring their respective particles at spacelike separated locations. To maintain locality, Rovelli argues that Alice and Bob cannot regard events lying outside their past light-cones as physically real.[104] I argue, instead, that relational quantum mechanics does not need to restrict elements of reality exclusively to events lying within an observer's past light cone.

The idea that the beables relative to a given observer are to be restricted to events arising from the direct physical interaction between the observer and a particle has been criticized by Jacques Pienaar.[105] I will dedicate a few paragraphs to present Pienaar's criticism before returning to my main claim. Pienaar argues that one of the assumptions of RQM regarding locality is problematic. The assumption in question (which for shortness I will call 'assumption (3)', as in Pienaar's paper) reads: "all physically meaningful beables relative to an observer are located within that observer's past light-cone."[106] The problem with (3), as Pienaar explains, is that it is too vague to tell us which events within an observer's past-light cone ought to be considered as physically meaningful. To explain his point, he makes the example of an observer *O*, located on Earth, observing Mars through a telescope and witnessing the event of Alice stabbing Bob deep into his heart with a knife, on a location on Mars. Here, Pienaar distinguishes between two physical events: the event that arises from the physical interaction between Alice

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[104] P. Martin-Dussaud, C. Rovelli and F. Zalamea, 'The Notion of Locality in Relational Quantum Mechanics', p. 5.

[105] J. Pienaar, 'Comment on "The Notion of Locality in Relational Quantum Mechanics"'.

[106] J. Pienaar, 'Comment on "The Notion of Locality in Relational Quantum Mechanics"', p. 1.

and Bob, taking place on Mars (called ‘event *M*’), and the event that arises from the interaction between the light quanta and the observer’s telescope (called ‘event *W*’). The question that Pienaar poses is: how can the event *M* be regarded as a ‘beable’ relative to observer *O*? He concludes that, if we take Rovelli’s relational interpretation to its logical limit, then there is no way for *O* to regard the event *M* as physically real without depriving locality of a meaningful definition within such a framework.

The reason is, as Pienaar argues, that ‘assumption (3)’ is too vague to tell us which events lying within the light cone are to be considered physically real for *O*: if, as Rovelli would argue, events are actualized through physical interaction between two physical systems, and the reality of such events is relative to the systems involved in the interaction, then only the event *W* is to be regarded as physically meaningful relative to *O*, while the event *M* is not, because though such an event lies within *O*’s past light-cone, it does not arise through direct physical interaction between *O* and Alice/Bob, therefore according to relational quantum mechanics *O* cannot regard it as physically meaningful: it is a beable only relatively to Alice and Bob because they are physically involved in event *M*. Therefore, how is it possible for *O* to regard *M* as a beable?

Pienaar makes two attempts to strengthen ‘assumption (3)’: firstly, he strengthens it as: “All physically meaningful beables relative to an observer are located within that observer’s past light-cone, *and all beables in the observer’s past light cone are physically meaningful to that observer*.”[107] However, Pienaar further points out that this version of the assumption allows us to state that a beable comes into existence when it is possible, *in principle*, for information about such a beable to reach the observer: the problem is that this statement implies that the notion of past light-cone refers to the speed of light traveling in a vacuum, but nowhere in the universe is a true vacuum to be found, therefore a beable would become ‘physically

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[107] J. Pienaar, ‘Comment on “The Notion of Locality in Relational Quantum Mechanics”’, p. 5.

meaningful' for the observer just a moment before the light quanta reach him in any realistic circumstance.[108]

Pienaar makes a second attempt to strengthen (3) and recognizes that such strengthening is also problematic because it would commit the relational interpretation to a form of solipsism (for reasons that will become clear in the following). The further strengthened statement reads: "All physically meaningful beables relative to an observer are located along that observer's past *world-line*."[109] The problem that Pienaar recognizes about the latter assumption is that since each observer is associated with its own set of beables, then there are several distinct sets of beables, each physically meaningful only for their respective observers and there is no clear way to combine such different world-lines into a unified framework.

Pienaar proposes a way out of this dilemma:

> One way to achieve a unified picture is to introduce the idea […] of an 'abstract beable': an occurrence which is not necessarily directly witnessed by an observer but is inferred to have happened 'elsewhere', and which can then be assigned a space-time location.[110]

However, he points out that this would be no solution at all because it would be equal to claim that Bell's theorem applies to 'abstract beables' and not beables which are supposed to stand for physically real events.

I think that Pienaar's criticism does not apply because both he and Rovelli implicitly share the idea (which I think is problematic) that 'measurements' in quantum mechanics can be either direct or indirect (here, I intend 'measurement' as a special case of interaction involving a physicist utilizing a physical system, either microscopic or macroscopic, to check

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[108] J. Pienaar, 'Comment on "The Notion of Locality in Relational Quantum Mechanics"', p. 5.
[109] J. Pienaar, 'Comment on "The Notion of Locality in Relational Quantum Mechanics"', p. 6.
[110] J. Pienaar, 'Comment on "The Notion of Locality in Relational Quantum Mechanics"', p. 9.

the values of certain quantities of another physical system). Of course, RQM is not about measurements in the first place, but about more general interactions. On the other hand, we should be able to test intuitions about RQM by taking the special case of measurements (and Pienaar's example clearly involves a measurement).

To be clear, the criticism advanced by Pienaar would make perfect sense if measurements in quantum mechanics could be understood as ‘direct’ measurements. In Pienaar’s example, we can say that observer *O* ‘directly’ measures a property of the photon (that is, directly interacts with it and realize a property relative to such interaction) that landed on his eyes from the surface of Mars, therefore he will regard as physically real the event *W* that took place through the immediate interaction between the photon and himself. However, *O* ‘indirectly’ witnesses the event *M* happened on Mars (because the image of that events had been ‘carried’ by the photon), which is a real event from the perspective of Bob who was physically involved in *M*. According to Pienaar’s criticism, within the framework of relational quantum mechanics, *O* cannot regard it as a beable, unless we admit that Bell’s theorem is about abstract beables. What I intend to criticize is Pienaar’s implicit idea that there is some important difference between directly and indirectly witnessed quantities. I argue that there is nothing ‘abstract’ about ‘abstract beables’ because, as I claim, the difference between directly and indirectly witnessed quantities is ill-founded: with every measurement that we perform on a particle, we always ‘indirectly’ witness the quantities of the particle that we wish to measure.

To recall what we mean by direct and indirect measurements, consider the following two sets of interactions: a physical interaction between the object to be measured and the measuring device and a subsequent physical interaction involving the device and the observer. To be clearer on the meaning of the terms that I use, by the term ‘direct measurements’ I intend that these two sets of interactions are independent of each other, whereas if measurements are indirect (and I claim that this latter is the proper notion to take into account in this discussion), these two sets of interactions are not independent of each other. Therefore, if measurements were understood as ‘direct measurements’, then the observer would not ‘directly’ measure the spin of the particle (and, thus, cannot regard it as physically real) but only the ‘outcome’ displayed by the measuring device. The latter would be the only event to which the observer can ascribe an element of reality. To make an analogy with Pienaar’s example, the event in which the observer ‘looks’ at the outcome shown by the measuring device is analogous to the event *W* (the light quanta colliding with the observer’s eyes) which the observer considers as physically meaningful, and the event in which the particle interacts (and establishes a certain property in relation to it) with the device is analogous to the event *M* (Bob’s murder on Mars). Therefore, how can we ascribe an element of reality to the spin of the particle (the event *M*, that is the particle having ‘spin up’ in relation to the interaction with the measuring device) starting from the outcome shown by the device (that is the event *W*, the interaction between me ‘looking’ at the device and the device itself)? To repeat once again, if measurements in quantum mechanics are understood as direct measurements, then there would be no way to do so.

As I attempted to show in the course of the previous sections of this thesis, following Guido Bacciagaluppi’s analogy between Bohr’s single and double slit and Hermann’s treatment of the γ-ray microscope, holding on to the notion of ‘direct’ measurement would imply that these mentioned cases were different. As I explained in the previous sections, I rely on Bacciagaluppi’s analogy between these cases of measurement to claim that the idea of ‘direct’ measurement in quantum mechanics is untenable: there is no difference between a case in which we perform a measurement on a particle through a measuring device, and measuring one particle by employing a second particle because, in both cases, we reconstruct some of the features of the original interaction depending on how we physically interact with the latter object. I claim, based on this analogy, that all quantum measurements are indirect: if in RQM we want to ascribe an element of reality to the spin of a measured particle, then we cannot ascribe elements of reality only to systems that the observer witnesses directly (the ‘outcome’ displayed by the measuring apparatus). Note that in talking about ‘object to be measured’, ‘measuring device’ and ‘observer’, we are not assuming that one is classical or macroscopic and the other purely quantum: in talking about their ‘classical’ features, we need to be careful in choosing which of the complementary classical concepts we wish to use in describing certain aspects of the interaction in question (complementary in the sense of a selective application of classical concepts, following Howard’s reconstruction of Bohr’s doctrine of classical concepts and the analogy with Grete Hermann’s treatment of the γ-ray microscope).

I will now formulate the point concerning the EPR correlations in the relational interpretation and show that Pienaar’s criticism does not apply if we consider measurements in quantum mechanics as ‘indirect’ measurements.

Before proceeding, let me briefly recall Rovelli’s treatment of the EPR correlations. According to Rovelli, when the two particles are prepared together in the singlet state, relatively to Bob and Alice, they have no individual property because the individual particles have not yet interacted with Bob’s and Alice’s respective measuring devices. When the two particles leave the region of their initial preparation, Bob and Alice will adopt a quantum state to predict the probability of the individual particles having certain values at the time of their future interaction with the device, but such a quantum state does not tell us what happens before the particles reach the detectors: in the spirit of the relational interpretation, simply nothing ‘actual’ is happening (relatively to Alice and Bob).

Once one of the particles interacts with (say, Bob’s) device, then such a particle will have a definite property relative to the interaction with the device. At this point, Rovelli argues that the EPR correlations can be conceived as a challenge to Einstein’s realism rather than to locality because Bob can ascribe an element of reality only to events that take place through direct physical interaction with himself and not to Alice’s outcome (that is an event taking place within Alice’s light-cone, not Bob’s): as I have already stressed in the preceding sections, according to Rovelli there is no ‘view-from-nowhere’ that would allow one to do so (and in this latter case, there would indeed be a violation of locality). Bob can, however, rely on the quantum state that he adopts after measuring his particle to predict probabilistically what will be the outcome of the next interaction: either between himself and Alice's particle when he heads to the other region to measure it himself or when he meets again with Alice to discuss the outcomes they obtained (according to Rovelli, the communication between them is ultimately a 'quantum' process: it is an interaction between particles). He furthermore argues that these correlations may be explained through a common cause between them, from the perspective of a terminal observer *O* located in the common future light-cone of Alice and Bob.

We can see that in this discussion of the EPR correlation, measurements are presupposed to be 'direct'. The particle reaches Bob's device and a certain property is established (either spin up or down) relative to the interaction between the particle and the device. Then, Bob arrives in the proximity of the device and looks at it (that is, he physically interacts with it) and sees 'spin up'. However, the property 'spin up' in this new context is a relational property between Bob and the measuring device, not between Bob and the measured particle (recall Pienaar's example of the observer witnessing Bob's murder on Mars). Therefore, by saying 'spin up', Bob is referring to the outcome shown by his device and not to the particle 'being spin up' relative to his device (that is, the property of the particle realized through the former interaction between itself and the device).

Let us now look at the case in which we understand measurements as being 'indirect' measurements. In this case, we need to have clear in mind that there is no difference between a case in which Bob alone measures one particle through a measuring device and one in which Alice and Bob measure their particles at spacelike separated regions (recall the analogy of the single-slit and double-slit experiments in Bohr's reply to EPR). It is also important to clarify that there is a difference between my formulation of the EPR scenario and Rovelli's own, regarding where the elements of reality can be located (within and outside the lightcone), which will become clear later in this section. To explain this, let us start with Bob measuring a single particle and let us introduce Alice later in the story.

A particle arrives at Bob's device. Just before the particle hits the device, Bob is wrapping his mind around one of the thorniest mysteries of the universe (if there is one!): was this particle a corpuscle or a wave? Does it have spin up or spin down, or will it become real only upon interaction with the device? And so on. Suddenly, the reading on the display of his measuring device switches from 'ready' to 'spin up', and Bob's mind is immediately flooded with many other questions: 'what has just happened?', 'what is it that I am looking at?' At first, he is tempted to regard as physically real the mere reading of his apparatus and avoid questions about the ontic status of the particle he wished to measure: the display of the measuring device is what he is looking at (or physically interacting with), in the end.

However, he decides not to stop there. He dismantles his device to see what happened in it: he wants to access the causal chain of events that brought the particle to cause the reading 'spin up' in the display of the device. Bob will be able to reconstruct a causal succession of events (or, importantly, the possibility of reconstructing such a causal story is at least not precluded in principle. This would be the case if, for example, we attempt to reconstruct the causal story of the exchange of momentum when we measure position because they are complementary quantities): in a few words, he recognizes that the measuring device displays 'spin up' because it was the particle 'being spin up' that caused the device to react in a certain way. However, we do not say that there is a context-independent matter of fact about the particle already having 'spin up' during its path towards Bob's device. That is, if we recall Grete Hermann's insistence that causality and the criteria of its application need not be tied together, then it is pointless to ask about a causal story about the particle and the device without previously entering ourselves into such a context of observation.

The point I wish to make is that through Grete Hermann's insight about the relative character of quantum-mechanical descriptions and causation (which I have shown in the previous section to be in line with Rovelli's idea of causation in an indeterministic framework, with the difference in Hermann that this notion of causation can be classical, if we respect complementarity intended as selective use of mutually exclusive classical notions in describing the interaction), it makes perfect sense to speak about a causal story that brought the outcome about, and thus to regard, retrospectively, the spin of the particle as a beable relative to such a context. To be clear, I am not claiming that the particle already had a definite spin (or position or momentum) before physically interacting with the measuring apparatus and that the latter merely 'read' or 'reveal' such a value of the particle: this sort of claim would imply that there is a 'matter of fact' (or a 'context independent' state of affair of the system) as to whether the particle possesses an objective property or not. However, recalling Hermann's insistence on the relative character of quantum mechanics it makes sense to say that, after defining a context of observation with respect to the interaction between the particle and the device, relative to such a context the particle was 'spin up' during its path towards the device: once the interaction has taken place, we can always find, in principle, the causes that brought the outcome about, but it does not make sense to ask about the spin of the particle without entering the relevant context of observation.

Now, let us introduce Alice in the story and reformulate the EPR scenario in the relational interpretation according to the insights just presented. Initially, Alice and Bob prepare the two particles in the singlet state. Let us accept (following Rovelli and Hermann) that it is pointless to ask about the spin of a specific particle, because they have yet to individually interact with Alice and Bob, so there is no context of observation in which the individual particles have a value relative to Alice or Bob. Based on this initial interaction, Alice and Bob only know that the particles' net angular momentum is zero. Now, Alice and Bob operate their measuring devices at two spacelike separated regions and measure the spin of their respective particles. Here is the crucial point: what can Alice and Bob regard as physically real relative to themselves?

Bob reconstructs, in retrospection, the causal story of the outcome he obtained, starting from the time of measurement and tracing it back to the singlet state preparation. Now (and only now!) can he say that this particular particle was spin up all along its path, relative to his context of observation. To be clearer: there is no view-from-nowhere or a context-independent matter of fact about the particle having had spin up all along its path to Bob's device. But once Bob has performed a measurement, he enters a context of observation (to borrow again Hermann's words) relative to which he is in the position to say what caused his device to display spin up.

We do not need a context-independent causal explanation to account for the particle having spin up at the time of measurement if we borrow Grete Hermann's lesson about the relative character of causality and quantum-mechanical descriptions. But what about the reality of Alice's particle relative to Bob? If Bob's particle was found to be spin up upon measurement, and if he reconstructs the causal story behind his outcome back to the initial singlet state preparation, he realizes that (relative to this context!) the other particle must have had 'spin down', so he retrospectively ascribes an element to reality to the other particle's spin to the time of their initial preparation: in other words, Bob's particle is acting as a measurement device for measuring the other particle's spin. However, the second particle had taken its path to Alice's measuring device, leaving Bob's past light-cone. Can Bob regard the spin of the other particle as physically real for him, since it is no longer located within his past light cone? Rovelli would argue that the second particle has no physical reality relative to Bob: "all physically meaningful beables relative to an observer are located within that observer's past light-cone." In contrast, we argue that this is not the case. Once Bob (or Alice) has ascribed an element of reality to the other particle by reconstructing a sequence of causal events starting from the context of observation he or she entered in after measuring his/her particle, why would such an element of reality be 'lost' upon the moment it has left one's light-cone? What we argue here is that the spin of Alice's particle can be considered physically real for Bob even after it leaves Bob's light cone.

Let me articulate this point a bit more. To provide a clearer explanation, let us look at the case in which we measure two incompatible quantities (position and momentum) on two entangled particles, relying on Hermann’s treatment of the EPR correlations. Let us prepare two particles in a maximally entangled state and suppose that Bob measures the position of his particle and Alice measures the momentum of her own. If position is measured on one particle, then through the correlations embedded in the quantum state we can infer, based on the result obtained, the precise position of the other particle. This goes in the same way for the case of measurement of momentum. Now, since position and momentum are complementary quantities, can we say that the position and momentum of the two particles are simultaneously well defined? To respond positively to this question would mean embracing Einstein’s position about the completeness of quantum mechanics. However, in this thesis I am addressing the frameworks of relational quantum mechanics and Hermann’s views, thus I will negatively answer this question. So, what happens when Alice and Bob meet in a common region of their future light-cones to discuss results?

Relying upon Grete Hermann’s account, we can say that when Alice and Bob measure their particles at spacelike separated regions they enter, respectively, two distinct contexts of observation. In one context, a measurement of position had been carried out on one particle, and relatively to such a context, we can reconstruct a causal story about the original interaction between the two particles that allow us to exploit position correlations of the entangled state. Relatively to the other context, we can reconstruct the exchange of momentum between the two particles, and thus we can exploit the correlations of momentum of such an interaction. Crucially, these two contexts of observation are different and are related to measurements taking place at spacelike separated regions, so we claim (following both Hermann and Rovelli) that these two contexts cannot be directly compared, therefore we avoid saying that momentum and position of the two particles are simultaneously determined in an ‘objective’ sense. When Alice and Bob meet, they enter into a new context of observation in which the comparison between the two old contexts becomes possible. Now, Alice and Bob can compare results: in doing so, to quote Bacciagaluppi,

> They *each lift the other's ignorance* about what the actual state is relative to the context of measurement they have just entered. When this is done, they both assign the same product state of one momentum eigenstate and one position eigenstate to the two particles as an individual description of the state of the particle pair relative to a context in which momentum and position have been measured on the two particles, respectively.[111]

What this means is that when Alice and Bob meet to discuss the results they obtained (a definite description of the correlations of the position of the two particles and an indefinite correlation of momentum in the case of Bob, and a definite description of their momentum correlation and an indefinite description of their position correlations in the case of Alice) they are no longer referring to the context of the original interaction between the two particles, but to their respective context of observation they entered at the time they measured their respective particles, which can now be put in comparison thanks to the new context they enter when they meet.

With this, I have attempted to show that by considering measurements as indirect measurements, elements of reality do not need to be ascribed solely to events within the past light-cone of an observer. We can rely on this insight to account for the EPR correlations and maintaining, at the same time, that the EPR case is not to be understood as a violation of locality in the framework of the relational interpretation. Here, I intend locality as Rovelli does: no causal influence between two spacelike separated events. In the sense of Bell, we have no violation of parameter independence: it is not the case that Bob's decision of setting the apparatus to measure the position of his particle caused the other particle to have no definite

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[111] G. Bacciagaluppi, 'Better than Bohr', (in preparation).

momentum. We do not need to violate outcome independence either: it is only when we insist, against Rovelli as well as Grete Hermann, that the two spacelike separated contexts of observation can be directly compared, that we see correlations between the outcomes obtained by Alice and Bob. To stress the point again: it is only when Alice and Bob meet in a common region of their future light-cone that they can compare results. When they meet, they agree that a measurement of position and a measurement of momentum have been performed and that some outcomes have been obtained from such measurements. However, what Alice and Bob will disagree on is the temporal order in which they, respectively, ascribe elements of reality to the measured quantities of the particles: from the perspective of Bob, the positions of the two particles enter in his past light-cone before the elements of reality corresponding to the momentum of the particles as measured by Alice (he needs to wait to meet her first). For the perspective of Alice, who measures momentum, she ascribes an element of reality to their momentum before meeting with Bob and ascribing an element of reality to the position of the particles. This is not because one measurement has been performed earlier in time than the other (the theory of relativity holds that there is no privileged or absolute time ordering of two events taking place at spacelike separated regions, but this is not the point here), but they only disagree on the time order in which elements of reality are ascribed to the values of the particles.

4.2. Retrospective Stable Facts

In this subsection, I wish to analyze another possible consequence that my claims about indirect measurements and the possibility of retrospectively ascribing elements of reality to quantities of a particle at the time of its interaction with the measuring device bear with respect to a recent work from Di Biagio and Rovelli titled *Stable Facts, Relative Facts*. In this work, they claim that stable facts, which characterize the classical world we live in, are a subset of a wider class of ‘relative facts’, which thanks to decoherence have become approximately stable (meaning that their relativity can be ignored).[112] I claim that if we apply Hermann’s insights about retrospective causality (which I have shown can be applied to Rovelli’s view), then we may argue that in relational quantum mechanics, it is possible to understand ‘stable facts’ as relative facts that become stable once we retrospectively ascribe elements of reality to a particle by reconstructing the causal succession of events that brought the particular outcome about upon measurement. In other words, it is precisely when we retrospectively construct causal links between the interaction of a system A and B and a later interaction of A or B with C, that we consider the element of reality pertaining to A to be independent of whether we consider them relative to B or C. But first, I will explain what Rovelli means by ‘stable facts’ and what role they play in the ontology proposed by Rovelli in his relational interpretation of quantum mechanics.

Rovelli bases the relational interpretation of quantum mechanics on ‘relative facts’, that is, facts that are defined to happen whenever a physical system interacts with another physical system: “if an interaction affects F in a manner that depends on the value of a certain variable Ls of S, then the value of Ls is a fact relative to F.”[113] As I already explained in detail in the first section of my thesis when presenting Rovelli’s relational interpretation, all interactions between particles establish a relative fact, which means that the values of the suitable variables of two interacting particles become actualized relative to the interaction of these two particles, and not relative to another system which has yet to interact with the particles in question. Stable facts, instead, are intended as a subset of relative facts, whose relativity can be ignored:

> A relative fact about a system F is stable with respect to a system W if W has no access to a system $\mathcal{E}$ which is sufficiently entangled with F. But stability is only

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[112] A. Di Biagio and C. Rovelli, ‘Stable Facts, Relative Facts’, p. 1. For an introduction to decoherence, see: G. Bacciagaluppi, ‘The Role of Decoherence in Quantum Mechanics’, *The Stanford Encyclopedia of Philosophy* (Fall 2020 Edition), Edward N. Zalta (ed.), URL = https://plato.stanford.edu/archives/fall2020/entries/qm-decoherence/ .

[113] A. Di Biagio and C. Rovelli, ‘Stable Facts, Relative Facts’, p. 1.

> approximate (in principle, no fact is exactly stable for any finite ϵ) and relative (depends on how the 'observer' system couples to the system and the environment).[114]

To explain when a fact becomes stable relative to a given system, Rovelli invites us to recall the Wigner's friend scenario: imagine that a system *S* (it does not matter whether this system is classical or quantum because in Rovelli's interpretation all systems are ultimately quantum systems and the classical world is only 'approximately stable') interacts with a second system *F*. The system *F* will be affected in a way that depends on a particular variable of *S* named *Ls*, therefore the value of *Ls* becomes a 'fact' relative to *F*. This fact (*Ls* having a certain value relative to *S* and *F*), according to the relational interpretation, cannot be used to compute probabilities for the occurrence of facts relative to a third system *W* which has yet to interact with the coupled system *S* and *F* (relative to *W*, they will be in a superposition of states), because *Ls* is a relative fact between *S* and *F*.[115]

Now, what does characterize a 'stable fact'? As Rovelli explains, there are no, strictly speaking, facts that are 'absolutely stable' in the view of relational quantum mechanics (in the sense that facts are said to be stable relative to another given physical system), therefore there is no 'exactly classical world': 'relative facts' constitute the most 'fundamental' category of facts that characterize the ontology of relational quantum mechanics. Facts become 'approximately' stable thanks to decoherence: the suppression of quantum interference that happens when some information becomes inaccessible.[116] However, there are two subtle aspects of decoherence that Rovelli invites us to consider in order to understand why there are no 'exactly stable facts' in relational quantum mechanics: first, decoherence is a relative phenomenon, meaning that it depends on how a third system *W* interacts with the combined system in question: if a system *F* interacts with another system $\mathcal{E}$ (which stands for

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[114] A. Di Biagio and C. Rovelli, 'Stable Facts, Relative Facts', p. 3.
[115] A. Di Biagio and C. Rovelli, 'Stable Facts, Relative Facts', pp. 1-2.
[116] A. Di Biagio and C. Rovelli, 'Stable Facts, Relative Facts', p. 2.

‘environment’) and subsequently a third system W interacts with the combined system F and $\mathcal{E}$, the value recorded by W will be stable with respect to W, but if another system W' interacts differently with F-$\mathcal{E}$, it may be able to detect interference effects. Secondly, an event regarding F and $\mathcal{E}$ is stable with respect to a third system W even if the latter has not interacted with it.[117] In short, a variable Ls of a system S which gets sufficiently entangled with a large number of microscopic variables (forming $\mathcal{E}$, the environment) may become a stable fact for a third system W (say, the experimenter) if W has not interacted with $\mathcal{E}$.

It is interesting to note how the process of measurement is here described by Rovelli because (as I argue) it is compatible with the claim that all cases of measurement in quantum mechanics are EPR cases and involve a retrospective ascription of elements of reality to the value assumed by the variables of the measured particle. Rovelli gives the following treatment:

> If two systems S and F interact and their respective variables Ls and Lf get entangled, and if Lf is stable with respect to W, it follows immediately from the definitions that the stability of Lf with respect to W extends to Ls as well.[118]

Let S stand for ‘system to be measured’, F for ‘measuring device’ and W for the experimenter, the process of measuring S can then be divided into three phases:

> 1. An interaction between the system and the apparatus entangles Ls with a pointer variable Lf of the apparatus.
> 2. Lf gets correlated with a large number of microscopic variables (forming $\mathcal{E}$) that are inaccessible to the observer W.
> 3. The observer W interacts with the pointer variable Lf to learn about Ls.[119]

In terms of relative facts, this process can be phrased as follows: first, a relative fact is established between S and F; second, a relative fact is established between F and $\mathcal{E}$: since W

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[117] A. Di Biagio and C. Rovelli, ‘Stable Facts, Relative Facts’, p. 3.
[118] A. Di Biagio and C. Rovelli, ‘Stable Facts, Relative Facts’, p. 3.
[119] A. Di Biagio and C. Rovelli, ‘Stable Facts, Relative Facts’, p. 3.

has not yet interacted with $\mathcal{E}$ or *F*, this stabilizes the previous fact for *W*. Thirdly, the value *Lf* assumed by *F* becomes a fact for *W* and, since it is correlated with *Ls*, the value of the variable *Ls* also becomes a fact with respect to *W*.[120]

I argue that this framing of a measurement process is compatible with the claim (which I argue for in my thesis) that elements of reality are retrospectively ascribed to the value assumed by particles starting from the outcome of the measurement. First, to make the comparison clearer, let me recall once again the main claim on which my thesis is based: I argue that all cases of measurement in quantum mechanics are indirect measurements, so that also within the framework of relational quantum mechanics, we can ascribe elements of reality not only to the outcomes of measurements but to the value of the measured particle as well. This comes from Bacciagaluppi's claim about the analogy between the single- and the double-slit in Bohr's reply to EPR and the further analogy between Bohr's slit experiment and Hermann's treatment of the γ-ray microscope, in which Hermann has argued that depending on the further interaction between the photon and the photographic plate we can retrospectively check the causal story (respecting the uncertainty relations and therefore complementarity) about the measurement outcome in terms of the previous collision between the electron and the photon, once the relevant context of observation is defined.[121] In fact, in *Stable, Relative Facts* Rovelli explicitly characterized the measurement process in terms of entanglement between the established relative facts: first, a relative fact is actualized between the particle and the measuring device (corresponding to the first set of interactions of the indirect measurement explained earlier in the thesis) and, crucially, when *W* interacts with the device and the particle, a fact is established also with respect to *W*: "the value of *Lf* becomes a fact for *W* and, since it is correlated with *Ls*, the value of the variable *Ls* also becomes a fact with respect to *W*."[122]

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[120] A. Di Biagio and C. Rovelli, 'Stable Facts, Relative Facts', p. 3.
[121] G. Hermann, 'Natural-Philosophical Foundations of Quantum Mechanics', p. 255.
[122] A. Di Biagio and C. Rovelli, 'Stable Facts, Relative Facts', p. 3.

What I wish to argue, more precisely, is that it could make sense in relational quantum mechanics to consider a fact 'stable' when an element of reality is retrospectively ascribed to it, by checking the causal story that brought the measurement outcome (the 'fact') about. In fact, here Rovelli argues that if a fact (*S* having a particular value *Ls* relative to *F*) is established, then the experimenter will 'learn' about *Ls* and not merely about the outcome of the device. However, I argue that it is not decoherence that plays the major role in bringing the 'classical world' about: in agreement with Auffèves, it is not a large number of quantum systems that matters in bringing the classical world about (from which it would 'emerge'), but (using here Hermann's terminology) what matters is that we enter in a certain context of observation in which we can apply certain (complementary) aspects of the classical picture (the classical concepts that can be put in analogy with the unintuitive quantum ones given a context of observation). However, the classical concepts that we are allowed to apply to describe the interaction are always applied once we have entered the relevant context of observation, and therefore we ascribe elements of reality in retrospection when we check the causal story of the interaction. Therefore, it makes sense to claim that a fact, in relational quantum mechanics, becomes stable once elements of reality are ascribed to the physical interaction in question when we enter the relevant context of observation. This claim also goes along with Rovelli's claim that stable facts are not 'absolutely stable': it is only relative to a given context of observation that a fact can be regarded as stable and, to quote Auffèves, this fact can be checked and confirmed repeatedly as long as the context is not changed.[123]

To conclude this subsection, what I wished to argue is that with the process of measurement described in Rovelli's recent work *Stable, Relative Facts* where he explains how a relative fact between a system coupled with its environment can become a stable fact relative to a third system, it becomes clear that Rovelli would not find desirable to limit, in relational

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[123] A. Auffèves, and P. Grangier. 'Contexts, systems and modalities: a new ontology for quantum mechanics.' *Foundations of Physics* 46.2 (2016): 121-137, p. 131.

quantum mechanics, the ascription of elements of reality by the experimenter to the outcome shown by the measuring apparatus, but apply it also to the particle itself. Since a relative fact is established *at the time* of the physical interaction, and then it subsequently becomes stable with respect to the experimenter, then the experimenter is *retrospectively* ascribing an element of reality to the particle at the time of its interaction with the measuring device, which happened previously than the interaction between the experimenter and the measuring device when the element of reality is ascribed by the experimenter.

Section V - A Comparison Between Grete Hermann and Alexia Auffeves' 'Contexts, Systems and Modalities' Approach

In this section, I wish to highlight some points of comparison between Hermann's views about the relativity of quantum-mechanical descriptions and a recent proposal from Alexia Auffèves to recover the quantum formalism from an ontology of Context, Systems, and Modalities (CSM). To do so, I will show that Auffèves' notion of contextual objectivity, according to which the 'quantum state' is not ascribed to a system alone, but jointly to the system and its context, can be put in relation with Hermann's view about the contextual character of quantum-mechanical descriptions of physical systems, especially concerning her idea that since quantum descriptions that belong to different contexts cannot be directly compared, one cannot rely on the complete knowledge of the state of a system measured in a certain context to predict with certainty what will be the state of the system upon a successive measurement when the context is changed.

Firstly, I will dedicate a few paragraphs to an exposition of the CSM approach following Auffèves' presentation in *Contexts, Systems, and Modalities: A New Ontology for Quantum Mechanics* and *What is Quantum in Quantum Randomness?*. Secondly, I will compare some important points in Auffèves' proposal with Hermann's views. The features of Auffèves' ideas which I wish to compare with Hermann's are:

1. Objectivity of natural phenomena is recovered relative to a context (because in ascribing properties to physical systems in quantum mechanics, their context cannot be ignored);
2. Auffèves' idea that probabilities (and the indeterministic character of quantum mechanics) result from the fact that different contexts cannot be directly compared, nor the modalities pertaining to them (in her terminology, modalities belonging to different

contexts are not *mutually exclusive*). Therefore, we cannot predict with certainty the modalities that we will obtain from a system when changing context.

3. The idea that in an EPR experiment it is pointless to compare modalities belonging to the two spacelike separated contexts of Alice and Bob when they measure their respective particles until they enter a common context.

First of all, it is important to spell out Auffeves' ontology, since, as she has claimed in a recent workshop,[124] rather than 'starting with the formalism' to understand what picture of the physical world we can draw from it, she intends to provide a suitable ontology from which the quantum formalism can be made compatible with physical realism, in the sense that "[…] the goal of physics is to study entities of the natural world, existing independently from any particular observer's perception, and obeying universal and intelligible rules."[125]

The ontology proposed by Auffèves consists of three different entities: (1) systems, (2) contexts, and (3) modalities. Firstly, a system is defined as a sub-part of the world that can be isolated well enough to be studied (to which we can ask 'questions'). The second element is the context, which is defined as the ensemble of interacting systems. As Auffèves emphasizes, a context encompasses the system and the measuring apparatus (or the environment of the system) and has a classical nature in the sense that no other context is needed to specify it (it can be, for example, the setting of a classical apparatus, but as she explains 'a system can never grow up to the point of including the context', therefore it does not fully reduce to a 'measuring apparatus'.[126] This is a difference with Rovelli's formulation: in his recent work *Stable Facts, Relative Facts*, Rovelli explicitly states that he intends 'context' and 'contextuality' as in Auffèves, with the difference that in relational quantum mechanics a context need not be

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[124] A. Auffèves, 'Object based vs relation based ontologies in quantum mechanics' (2021, July 2). Retrieved from http://carnap.umd.edu/philphysics/conference.html

[125] A. Auffèves and P. Grangier, 'Contexts, Systems and Modalities', pp. 121-122.

[126] A. Auffèves and P. Grangier, 'Contexts, Systems and Modalities', p. 133.

classical: it does not matter which system plays the role of a context).[127] Finally, a modality corresponds to a set of answers that we can obtain from asking questions to a physical system in a given context (it is the outcome that we obtain from a measurement, whose description includes the measured system, for example a particle, and the context in which it is measured, for example how the knobs of the measuring apparatus are set or which physical quantity the device is set to measure on the particle). Importantly, modalities obtained in a given context can be fully reproducible and predictable as long as the context is not changed.[128]

As she explains, in order to make physical realism (the idea that physics studies entities of the natural world, existing independently of the subject) compatible with the formalism of quantum mechanics, the notion of 'object' must be reframed in the CSM approach, as measurement outcomes (modalities) are jointly attributed to the system and to its context: in classical physics, the ordering of questions that we ask to a system does not change the outcomes we obtain from measuring it and thus we can understand the system as possessing definite properties and ignoring the contextuality of its state, while in quantum mechanics this is not true. Therefore, in order to obtain a repeatable result, we need to specify the context in which a certain outcome has been obtained and within such a context we can repeatedly check and confirm such an outcome. In the CSM approach the 'quantum state' is attributed both to the system and its context, therefore within the same context we can understand the system as 'possessing' a certain property, in agreement with physical realism:

> The certain and repeatable outcome obtained after a measurement manifests the existence of a physical "state." For CSM, this state does not characterize the sole system as usually considered, but it is attributed jointly to the system and to the specified context, including e.g. the orientation of polarizers or magnets. To underline this difference we call this "state" a modality.[129]

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[127] A. Di Biagio and C. Rovelli, 'Stable Facts, Relative Facts', p. 2.

[128] A. Di Biagio and C. Rovelli, 'Stable Facts, Relative Facts', pp. 2-3.

[129] A. Auffèves and P. Grangier, 'A Generic Model for Quantum Measurements'. *Entropy 2019,* 21, 904, p. 1.

Objectivity is understood in the CSM approach as a contextual notion because, within the same context, measurements of certain quantities of physical systems will give repeatable and predictable results (which she takes as a requisite for considering such a quantity as 'objective'), but "the "object" is the system and the context, and its "properties" are modalities."[130] She nicely characterizes the notions of 'quantum state' and of 'contextual objectivity' used in her account through the following statement:

> In general, states label both a system and a context. To distinguish them from classical states which are non-contextual, we call a contextual state a modality. As it is a phenomenon, the modality is as objective as a non-contextual state: this general ontology of states characterizes contextual objectivity. Because they are actual, modalities appearing within the same given context are mutually exclusive: if one is realized, the others are not. On the other hand, no conclusion can be drawn about modalities pertaining to two different contexts, because these two contexts cannot be simultaneously realized.[131]

Therefore, while in classical physics we can forget about the context of the systems we are studying (because the ordering of 'questions' does not influence the result of successive measurements, so the modalities one obtains from the system), in quantum mechanics the 'state' does not belong solely to the system: to say, for example, that a photon is polarized, we need to include in this description the setting of the measuring apparatus. An important consequence of the CSM approach that Auffèves points out, which makes her approach close to Hermann's view, is that we cannot predict with certainty which modalities we will obtain if we change context: modalities can be repeatedly obtained as long as the context is not changed, but when the context is changed, then we have a probabilistic relation between modalities

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[130] A. Auffèves and P. Grangier, 'A Generic Model for Quantum Measurements', p. 3.

[131] P. Grangier and A. Auffèves, 'What is Quantum in Quantum Randomness?', *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 376.2123 (2018): 20170322, p. 4.

belonging to the old context and those belonging to the new context, that is, they cannot be predicted with certainty from modalities belonging to the previous context.[132]

I will now analyze the CSM approach in relation to Hermann's views. The first interesting point of comparison between Auffèves and Hermann that I wish to analyze in more detail deals with the notion of 'context' and 'contextual objectivity' in Auffèves' account. In *What is Quantum in Quantum Randomness*, Auffèves and Grangier explain that, by definition, a context is characterized by non-contextual states: that is, it has a classical nature. Before being used as a context, an entity must have primarily played the role of a system. She writes that "[…] the probed entity used as a context is characterized by its own state, which does neither depend on some other context it would be embedded in nor on the system it may possibly contain."[133]

To compare this claim with Hermann, let us once again take as an example the case of the γ-ray microscope. In this example, the photon is used as a 'system' (to compare with Auffevès terminology) to probe an individual electron. Afterward, the interaction that takes place between the photon and the photographic plate (after the original interaction between the photon and the electron) will define the context of observation in which we can exploit some correlations (depending on which context we enter in) of the entanglement between the photon and the electron: depending on the further interaction that will take place between the photon and the photographic plate, we are able to reconstruct some aspects of the original interaction between the photon and the electron. That is, based on the latter interaction between the photon and the photographic plate (which defines a context), to use Auffèves' terminology, we are in the position to ask a certain set of questions to the system and relative to this context we will obtain a certain number of mutually exclusive modalities (in the sense that if one is true, then we know that the other is not): to say that the electron had a position at the time of the collision

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[132] A. Auffèves and P. Grangier, 'A Generic Model for Quantum Measurements', p. 2.
[133] P. Grangier and A. Auffèves, 'What is Quantum in Quantum Randomness?', p. 4.

with the photon is not to ascribe such property to the electron itself, but jointly to the electron and the context in which position has been measured and this context is defined from the further collision between the photon and the photographic plate.

Thus, we can find the idea that outcomes (or facts) are ‘objective’ relative to a context of observation defined by some particular physical interactions in both Auffèves and Hermann: in fact, Hermann herself has remarked that, say momentum of an electron, can then be checked by a separate measurement of the electron: as Bacciagaluppi explains, causal analyses

> […] cannot be applied prior to establishing the experimental context – which remains in principle undecided until the measurement is actually performed – thus such causal analyses cannot be used to predict the result of the measurement, and in this sense cannot be checked directly. However, they can be checked indirectly, because after the observation of the photon we can infer retrospectively that, say, the electron and the photon have exchanged a certain momentum. But then we can check this analysis by performing a further measurement of momentum directly on the electron. Our identification of the cause of one measurement result allows us to predict with certainty what the result of the other measurement will be.[134]

Therefore, the causal story which is retrospectively reconstructed after, for instance, we have measured the momentum of the electron, can then be checked by a separate measurement of the electron, provided one does not change the context.

Moreover, recall Grete Hermann’s ‘third case’ in her treatment of the γ-ray microscope, that is when no photographic plate is placed at all: here, Hermann recognized that the two particles are not individually described but are in an entangled state and therefore they cannot be characterized by individual states: “through this linear combination the light quantum and the electron are thus not described each by itself, but only in their relation to each other. Each state of one is associated with one of the other.”[135] This is because we lack a context of observation (in the sense that no interaction takes place which could define a context) in which

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[134] G. Bacciagaluppi, ‘Better than Bohr’, (in preparation).

[135] G. Hermann, ‘Natural-Philosophical Foundations of Quantum Mechanics’, p. 258.

we can say anything meaningful about properties of those particles: in this sense, it can be compared with Auffèves' claim that a system cannot be regarded as ~~a~~ having definite properties when its context is ignored, but that 'system plus context' can. One point to note is that Hermann did not explicitly characterize the notion of 'context of observation' as classical in nature in the same way as Auffèves, but it is clear, as I have already explained in the previous section, that according to Hermann it is relative to a context of observation that we can use 'quasi-classical' concepts that allow us to bring about a correspondence between the 'unintuitive' quantum-mechanical description of a physical system and the 'intuitive' classical concepts that we need to apply in order to account for the measured phenomena. In the appendix of her paper *Contexts, Systems and Modalities*, Auffèves has also emphasized the need to understand the world 'classically':

> "[…] in QM, macroscopic properties are required to describe phenomena, because the context cannot be ignored, due to the combination of the CSM and the quantization postulates introduced above. Therefore, for empirical consistency, the quantum system with its either mutually exclusive or incompatible modalities has to connect somewhere to the macroscopic world, where quantization does not show up at first sight."[136]

A second interesting point of comparison concerns the status of probabilities in quantum theory. In *What is Quantum in Quantum Randomness*, Auffèves explicitly claimed that in her view, quantum probabilities are not intended as epistemic, ignorance probabilities, but are a direct consequence of the CSM ontology and the quantum postulate: a context defines which sets of questions can be asked to a system and within this same context, we obtain a finite number of mutually exclusive modalities (in the sense, as explained above, that if one is true within such a context, then we know that the other is not within the same context). Therefore, when we go from one context to another, the modalities that we will obtain 'by asking

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[136] A. Auffèves and P. Grangier, 'Contexts, Systems and Modalities', p. 136.

questions' to the same system in another context cannot be predicted deterministically (and since systems do evolve continuously, their contexts do so as well): if we change the kind of questions we ask to a system, this equals to changing the context (for instance, asking what is the particle's spin measured along the z-axis and successively asking what is the particle's spin measured along the x-axis) and since modalities (the answers we get from the system and the context) belonging to different contexts are not comparable, then there is no way to deterministically predict which answers we will get from a different context based on the answer we obtained from a previous one. Therefore, within the CSM perspective probabilities are understood ontically and not due to our ignorance of the complete ID card of the system which would be hidden from us: randomness is a direct consequence of the fact that there are fewer available answers than possible questions: "the number of possible answers to all possible questions is larger than the number of allowed mutually exclusive answers for the considered system. As a consequence, some of the answers are not mutually exclusive (in the sense that they pertain to different contexts, and as such they cannot be directly compared), and thus must be related in a probabilistic way."[137]

Also in Hermann's view quantum mechanics is essentially an indeterministic theory, due to the uncertainty relations: since in her view quantum mechanics is already a causally complete theory (though indeterministic), she insisted that quantum-mechanical descriptions obtained in different contexts cannot be compared and that we cannot obtain a more 'complete' description of a physical system by combining different contexts, a point on which Auffèves has also insisted on.

It is important to note that while Hermann focused on the causal completeness of quantum mechanics (thanks to the recognition of the contextual character of the quantum-mechanical descriptions, which was the deeper claim in Hermann's writing according to Elise

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[137] P. Grangier and A. Auffèves, 'What is Quantum in Quantum Randomness?', p. 5.

Crull),[138] Auffèves did not explicitly discuss the status of causation, but it is clear from the CSM approach that since a modality (for instance, the momentum of a particle when the device is set to perform measurements of momentum) can be repeatedly obtained if the context is not changed, then it could make sense to apply Hermann's insight that relative to a context of observation there is a (local) causal story, which explains the measurement outcome, and that can be retrospectively checked. That Hermann's notion of retrospective causation makes sense in the CSM perspective may become even more evident from the claim (as I will discuss below) that within this framework the EPR correlations cannot be interpreted as a faster-than-light causal influence between the two particles, and therefore that the CSM approach does not allow for acausal or faster-than-light processes in the physical world. Furthermore, neither in Hermann nor in Auffèves can one use the knowledge of causes (or of modalities in Auffèves' account) obtained in a particular context to predict with certainty the value of some physical quantities of the system that will be obtained in a different context.

The last and most important comparison that I wish to make between Auffèves and Hermann is with respect to the EPR case. In her paper *Contexts, Systems and Modalities*, Auffèves makes the following claim:

> According to the above reasoning, after Alice's measurement on one particle from a pair of particles in a singlet state, the "reality" is a modality for Bob's particle, within Alice's context. But Bob may also do a measurement, independently from Alice, and then the "reality" will be a modality for Alice's particle, within Bob's context. Does that mean that we have two "contradictories" realities? Actually no, because these realities are contextual: for instance Alice's modality tells that if Bob does a measurement in the same context as Alice, he will find with certainty a result opposite to Alice's one (given the initial singlet state).[139]

The point is that there are no 'nonlocal' correlations between the two particles when one is measured in a spacelike separated region from the other if we do not directly compare the two

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[138] E. Crull, 'Hermann and the Relative Context of Observation', pp. 159-160.

[139] A. Auffèves and P. Grangier, 'Contexts, Systems and Modalities', p. 129.

spacelike separated context, but within one context we can nevertheless ascribe a ‘reality’ to the other particle.

> How to explain the strong correlations between measurements on the two particles? By the fact that after her measurement, Alice can predict with certainty the state of Bob’s particle; however, this certainty applies jointly to the new context (owned by Alice) and to the new system (owned by Bob).[140]

This bears strong similarities with Hermann: recall Hermann’s treatment of the EPR correlations I have presented in the previous section: Alice and Bob cannot compare their contexts of observation when they measure their respective particles in spacelike separated regions. We are faced with the problem of nonlocality only if we insist that these two different contexts can be directly juxtaposed. Auffèves continues her treatment of EPR with the following statement:

> However, there is some non-locality, in the sense that the result on one side depends on the result on the other side; but this is only through a (local) redefinition of the context, not through any influence at a distance onto the remote particle. Again, it is essential here to consider that the modality belongs jointly to the particle(s) **and** to the context, and not to the particle(s) only, otherwise one would be led to Bell’s hypothesis.[141]

Auffèves’ idea that the reality of Alice’s particle for Bob depends on Bob’s context and Alice’s system (it is attributed to Alice’s particle within Bob’s context) bears some important similarities with the proposal I give here in this thesis, which is inspired by Hermann: as I will explain in section V, my claim is that once Bob has performed a measurement on his particle, he can also ascribe an element of reality to Alice’s particle, but he can only do so retrospectively, relative to the context of observation he enters when measuring his particle. In

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[140] A. Auffèves and P. Grangier, ‘Contexts, Systems and Modalities’, p. 129.
[141] A. Auffèves and P. Grangier, ‘Contexts, Systems and Modalities’, p. 129.

Auffèves' treatment, in fact, the reality of Alice's particle is a modality that jointly belongs to Alice's system (the particle) and the context of Bob, and the same story goes for Alice. Contradictory realities only appear if we insist that these contexts (which are spacelike separated) can be put together to form a unified context, which is not possible: it becomes possible only when Alice and Bob meet again in a common context of observation.

Another point of comparison is that both Auffèves and Hermann understand measurement as a 'state preparation'. As Frappier points out, Hermann recognized (although only implicitly) that the microscope experiment is not only a measurement procedure, but a state preparation procedure:

> When the photon hits the photographic plate (the effect), we retrodictively assume that it followed from the photon's interaction with an electron (the cause). We can then test this hypothesis by using our results (e.g. the location of the interaction) to make a prediction as to the state of the electron *after* its interaction with the photon (for example, a prediction about the result of a future momentum measurement made on the particle). Hermann thus recognises and uses, although only implicitly, the fact that the microscope experiment is -as noted by Popper- not only a measurement procedure, but also a state preparation procedure – in order to confirm the causal narratives offered by quantum mechanics.[142]

Also Auffèves has explicitly stated that within the CSM approach, a measurement is understood as a state preparation: as she explains, measuring a modality means performing an ideal quantum-non-demolition measurement, and "[…] this is consistent with the idea that a modality is defined by the certainty in the initial context, and not by the uncertainty in the (yet unknown) next contexts."[143]

To conclude this subsection, I wish to point out that there is an important difference between Auffevès' view and Rovelli's, which was highlighted at an online conference, *New*

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[142] M. Frappier, 'In the No-Man's-Land Between Physics and Logic': On the Dialectical Role of the Microscope Experiment', in: *Grete Hermann-Between Physics and Philosophy. Springer, Dordrecht, 2016.* 85-105, p. 101.

[143] A. Auffèves and P. Grangier, 'Contexts, Systems and Modalities', p. 131.

Directions in the Foundations of Physics 2021.[144] In this conference, Auffèves herself has remarked an important difference between her proposal and Rovelli's relational quantum mechanics is that in the latter when different observers interact with a physical system, they may get different results: if Alice and Bob both make a measurement on the same system, these are two different sets of interactions and thus there is the possibility that they will describe the result of the interaction differently. In contrast, in Auffèves' view, different observers that enter the same context will all agree on the modality obtained (which can be obtained repeatedly). I claim that this makes Auffèves' view particularly close to Hermann's, especially to Hermann's idea that objectivity of facts is regained relative to a context of observation, which I have discussed earlier in the thesis (which was also close to Bohr's view that objectivity of phenomena can be recovered relative to a particular experimental arrangement and observational context).

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[144] A. Auffèves, 'Object based vs relation based ontologies in quantum mechanics' (2021, July 2). Retrieved from http://carnap.umd.edu/philphysics/conference.html

Conclusion

I have started my thesis by characterizing the notions of ‘measurement’ and ‘locality’ in the relational interpretation of quantum mechanics and I have claimed that Rovelli relies on the idea that measurements in quantum mechanics should be understood as ‘direct’. Instead, I have claimed that this characterization of measurements is not the proper one: I have discussed, relying on some works by Guido Bacciagaluppi, the analogy between the single- and double-slit experiments in Bohr’s reply to EPR and the further analogy of Bohr’s analysis with Grete Hermann’s treatment of the γ-ray microscope to show that measurements should be understood, rather, as indirect measurements. From these considerations, I have claimed that Alice can ascribe an element of reality to the distant particle in the EPR scenario without violating locality, intended as the principle forbidding a mutual instantaneous physical influence between spacelike-separated events.

The reason why I have claimed that locality can be maintained even in the case Alice ascribes an element of reality to Bob’s distant particle is that Alice, starting from the outcome she obtains by measuring her particle, works in retrospection to find the causes of her measurement outcome and therefore that there is no problem with locality intended as ‘no mutual physical influence between spacelike-separated events’ within the framework of relational quantum mechanics because this procedure is always done in retrospection. In claiming that the causes of a measurement outcome can be found in retrospection, I have relied on Grete Hermann’s account of the relative context of observation and shown that Hermann and Rovelli share similar ideas with respect to the relativity of quantum-mechanical descriptions. Therefore, retrospective causality, which Hermann saw as a natural consequence of the fundamental relativity of the quantum-mechanical descriptions of a system to a context of observation, can fit Rovelli’s framework as well and enrich the way Rovelli and other authors claim that it is possible to causally account for the EPR correlations by means of a common cause between the outcomes and maintain the principle that causes and effects are not further away than permitted by the velocity of light.

As I have claimed, the notion of causality in relational quantum mechanics lacks a precise characterization in the authors' treatment of the EPR correlations, and they limit themselves in claiming that 'nonlocality' reassumes the difficulty of understanding causality and indeterminism in the same conceptual framework. Hermann has discussed precisely this issue in her 1935 essay and argued that indeterminism does not force us to reject causality in the natural world, but rather it clarifies it.[145] Therefore, in relational quantum mechanics, I maintain that in the EPR scenario (which is not a fundamentally different scenario from the one in which we measure a physical quantity on a single particle) the correlated outcomes can be causally explained in retrospection by relying on Hermann's retrospective causality.

To conclude this thesis, I wish to claim that the ideas expressed by Hermann in her 1935 essay can have implications for present-day discussions concerning measurements, causality, and locality in quantum mechanics, as in the case of the relational interpretation and Auffèves 'Contexts, Systems and Modalities' approach. I share Léna Soler's claim that if Hermann's essay had enjoyed more popularity, the history of the interpretations of quantum mechanics would have been different. In comparing, for example, Hermann's and Bell's criticism of von Neumann's proof, Soler has claimed that:

> […] despite the fact that Bell's paper quickly convinced all physicists after its publication, Hermann's refutation had no impact. In fact, it remained entirely unknown – and this is highly surprising if one bears in mind that physicists such as Heisenberg and von Weizsacker must have known of it. Whatever the reason may be, this has important historical implications. Indeed, if Hermann's refutation of Neumann had not been a 'dead letter', the history of interpretations of quantum physics would certainly have been very different.[146]

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[146] L. Soler, 'The Convergence of Transcendental Philosophy and Quantum Physics', p. 92.

Therefore, this thesis can be conceived as an attempt to bring Grete Hermann’s ideas into present discussions concerning certain interpretations of quantum mechanics, especially regarding the relational interpretation, and to encourage authors to reflect on her views, which are not merely outdated, historical ideas, but they can still be of interest and have an impact on contemporary discussions concerning the foundations of quantum mechanics.

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