An analysis of Relational Quantum Mechanics

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Abstract

In this thesis, I argue that no current version of Relational Quantum Mechanics (RQM) both meets its own goals and solves the problem of measurement, and the prospects that any such interpretation could be articulated are not promising.

I offer a clear illustration of the core framework of RQM and I note that all versions of RQM share an ontology of systems and events, where an event consists of a variable of a system taking a value relative to another system. An important difference can be drawn between versions of RQM which take the occurrence of events to be relative and those which take it to be absolute.

I argue that if RQM is to solve the measurement problem, it needs to specify the circumstances in which events occur. The primary literature does not offer such a specification, therefore I endeavour to construct one, accounting for both possibilities of the relative or absolute occurrence of events. I explore two avenues, which are suggested by plausibility as well as remarks in the primary literature.

First, I consider an intuition stated in Rovelli's original formulation of RQM that the occurrence of an event involving two systems is indicated by the appearance of correlations in the quantum state relative to a third system. Unfortunately, I argue that this intuition fails to provide an adequate specification for the (relative or absolute) occurrence of events.

The failure of the correlation-based intuition suggests a different approach which is more in touch with physical practice and apparently favoured by recent writings on RQM, namely appealing to the structure offered by the dynamics. The development of this approach prompts a much needed discussion of the status of the dynamics in RQM and I argue that, given the basic framework of RMQ, the Hamiltonian must be conceived as relative to a system, just like the quantum state. Unfortunately, I conclude that the dynamics does not offer an adequate principle to specify the circumstances in which events (relatively or absolutely) occur.

Interestingly, some arguments indicate that for the occurrence of events to be absolute, it may be necessary to introduce a global collapse of the wave-function or many worlds.

The search for a principle which defines the circumstances of events turns out to be mostly divorced from the question of which variable becomes determinate at each event, namely the preferred basis problem. I argue that, under the (unlikely) assumption that a plausible account of the circumstances of events is available, there are hopeful signs that a correlation-based rule coherent with RQM's framework and aims may be formulated. However, the question of whether the rule picks out empirically adequate bases is not addressed.

Contents

Chapter 1

Introduction

It's been almost 20 years since the Relational interpretation of Quantum Mechanics (RQM) was introduced by Carlo Rovelli (Rovelli, 1996). Over time, the interpretation has developed and changed significantly. Even so, several essential parts of RQM are still undefined or ambiguous. In this thesis, I argue that the current formulations of RQM do not solve the problem of measurement. Moreover, I argue that the prospects of articulating a version of RQM which both meets its own goals and solves the measurement problem are not promising.

In brief, the problem is the following. All versions of RQM explain the world in terms of an ontology of systems and events, where an event consists of a variable of a system taking a value relative to another system. I argue that, in order to solve the problem of measurement, RQM needs to offer a specification of the circumstances in which events occur, but current formulations do not offer an adequate specification. I also show that the most plausible ways of offering such a specification fail, therefore I claim that the prospects of articulating a version of RQM which both satisfies its aims and solves the problem of measurement are dim.

1.1 The structure of the thesis

I begin the analysis of RQM in Chapter 2 with a precise and faithful account of the core framework of RQM, avoiding controversial or ambiguous parts of the theory. I note that all versions of RQM are founded upon the same ontology of systems and events, where an event consists of a variable of a system taking value relative to another system. The status of events is cause for an important distinction between different versions of RQM since the literature is divided on whether the occurrence itself of events ought to be considered as relative to systems (Rovelli, 1997, Smerlak and Rovelli, 2007, Rovelli 2018), or absolute (Adlam and Rovelli, 2023). In this thesis, I do not take a stance on this issue, rather I attempt to resolve the problem of measurement for both approaches to RQM. After offering an account of the basic framework of RQM, I also precisely define a 'consistency condition' (Rovelli, 1996, p.1652) which is assumed and enforced upon the basic framework throughout the primary literature. As opposed to what is suggested by Rovelli, I argue that the condition does not 'follow directly from quantum theory' (Laudisa and Rovelli, 2019).

I then begin Chapter 3 by considering the relevance of Bell's (1990) statement of the measurement problem for RQM and I briefly reject some of Oldofredi's (2023) claims concerning how RQM dissolves such a problem. Instead, I argue that for RQM to solve the problem of measurement, and, more generally, for RQM to be an adequate interpretation of quantum mechanics, a specification of the circumstances in which events occur must be provided, as well as a specification of which events occur in which circumstances. I argue that such a specification needs to meet two requirements, namely (i) it must specify the interactions relevant to the explanation of all successful applications of quantum mechanics in their appropriate order, and (ii) it must justify the claim that interactions occur between all kinds of systems and outside of experimental contexts.

In regard to this specification, the primary literature only establishes that a pair of events occur whenever two systems interact. However, since no effort is made to specify the circumstances in which interactions occur, the problem is only shifted from events to interactions. In the rest of the thesis (Chapters 4, 5 and 6) I attempt to construct a principle for the determination of the circumstances for the occurrence of interactions.

First, I explore whether it is possible to specify the circumstances in which interactions occur by appealing to correlations in the quantum state. This approach to interactions is suggested by several remarks in Rovelli's original formulation of RQM (Rovelli, 1996, 1997), which indicate a close-knit connection between an interaction between two systems and correlations appearing in the quantum state of the two systems relative to a third system. I consider three natural ways to implement the intuition that interactions just are correlations, covering both the relative and the absolute conception of the occurrence of interactions. Unfortunately, for both conceptions of interactions, the principles thus constructed fail to provide an adequate specification for the circumstances in which interactions occur.

The failure of the correlation-based approach suggests a different avenue, namely appealing to the dynamics. I explore this approach in Chapter 5. I first attempt the challenge of using the dynamics to define interactions within the simpler framework of absolute quantum states and dynamics. In this standard context, I obtain hopeful results, albeit not definitive. However, extending these results to the context of RQM turns out to be difficult, and likely impossible.

Before attempting such a task, one needs to make sense of the dynamics in RQM. Thus, I first endeavour to explore the complexities of defining a dynamics in RQM, filling a lacuna in the current literature on RQM. I argue that, within the context of RQM, the Hamiltonian must be conceived as relative to a system, much like the quantum state.

Once a well-defined picture of the dynamics in RQM is laid down, I explore whether one may define a specification for the occurrence of interactions from it. Unfortunately, it does not seem possible to do so, for either case of the relative or absolute occurrence of interactions.

Interestingly, I put forward some arguments which indicate that if the occurrence of events is taken to be absolute, it may be necessary to either introduce a global collapse of the quantum state, or many worlds. I note that, even though both options directly contradict the central aims of RQM, the many worlds option allows for a natural notion of relative quantum states.

The search for a principle which defines the circumstances of events turns out to be mostly divorced from the question of which variables become determinate at each event, namely the preferred basis problem. As this is also part of RQM's problem, I dedicate Chapter 6 to the discussion of the problem. First I note that the literature fails to successful address the problem, including the recent paper by Adlam and Rovelli (2023). Then, under the (unlikely) assumption that a plausible specification of the circumstances for the occurrence of events is available, I find hopeful sings that a correlation-based rule coherent with RQM's frameworks may be formulated. However, the difficult question of whether the rule picks out empirically adequate bases is not addressed.

I sum up the results and conclusions in Chapter 7.

1.2 The secondary literature

Before I get into the details of the arguments, it's worth remarking on the secondary literature on the topic. As explained above, this thesis deals primarily with the problem of specifying the circumstances for the occurrence of events in RQM. I am not the only one pointing out the difficulties that RQM faces in explaining when and which events occur. Muciño et al. (2021, 2022), Brukner (2021), Pienaar (2021), Healey (2022) and Lahti and Pellonpää (2023) all point out that RQM faces the preferred basis problem, even though they do so in very different ways. However, the problem with RQM is much deeper than defining a preferred basis for each event: it is not even clear when events occur. Only Muciño et al. (2021, 2022) touch upon this deeper problem and they agree with my analysis that, at least up until the publication of their paper, RQM did 'not provide enough resources to determine what counts as an interaction, when interactions happen, and which variables acquire values' (Muciño et al., 2021, p.12). Nonetheless, my contribution to the literature differs significantly from all of the above.

Firstly, due to the unclarity of the original literature, the papers just mentioned often face the problem that one may not be exactly sure of what the target view is, whether it is really the view held by Rovelli and his collaborators, and how it relates to the whole of Rovelli's enterprise.

In this thesis, significant efforts are spent to set out a precise basic framework for RQM, with particular attention to faithfulness to the literature. As opposed to (most) of the authors mentioned above, I have available some important papers (Rovelli, 2021, 2022; Di Biagio and Rovelli 2022; Aldam and Rovelli, 2023) which offer extensive and helpful clarifications on several aspects of RQM. With a clear basic framework set out, it's easier to see how the different parts of the theory may, or may not, fit into a coherent whole.

Moreover, although Muciño et al. (2021, 2022) do note the problem I focus on, in this thesis I go beyond showing that the current primary literature does not address the problem. Indeed I endeavour on a constructive project to find and propose the most plausible ways to specify the occurrence of interactions consistently with RQM's framework and aims. It is only in light of such failed efforts, that I can claim that the prospect of RQM solving the measurement problem while meeting its principal aims are dim.

Chapter 2

The core of RQM

This chapter offers an introduction to the core elements of RQM. First, I will outline the aims of RQM, which will also offer useful bounds on how the theory may be made precise and developed in the following chapters. Secondly, I will offer an outline of the basic framework of RQM, which is shared across the different versions of RQM. Finally, I will formulate a condition (Internal Consistency) which the primary literature enforces consistently on the basic framework and I will note that, contrary to what Rovelli and Laudisa suggest (Rovelli, 1996, Laudisa and Rovelli, 2019), the condition does just follow from quantum theory, on its own. This latter commentary on the Internal Consistency condition also offers an opportunity to present the Wigner's friend scenario, which is a thought experiment central to the motivation of RQM.

2.1 The aims of RQM

Ultimately, Rovelli and his collaborators hope to offer an interpretation with the following, arguably attractive, features:

> 'It is a realist view that is compatible with relativity; it does not require us to add anything to the existing mathematical framework of quantum mechanics; it is a robustly naturalistic picture that does not attach any special significance to conscious minds or measurements; and it refrains from postulating unobservable, inaccessible levels of reality like hidden variables or other branches of an Everettian multiverse. Moreover, it seems likely that RQM will still be applicable in the context of relativistic quantum mechanics, quantum field theory, and quantum gravity' (Adlam and Rovelli, 2023 p.2)

For future reference, it is convenient to clearly list the aims:

1. RQM gives no special significance to agents,[1] measurements or minds.
2. RQM does not assume a classical/quantum divide.[2]
3. RQM does not require one to modify or add anything to the orthodox mathematical framework of QM.
4. RQM does not posit any hidden variables.
5. RQM is a single-world theory.

[1] See Laudisa and Rovelli (2019, section 1.2).
[2] See Laudisa and Rovelli (2019, introduction).

6. RQM is compatible with the theory of relativity.
7. RQM is applicable in the context of relativistic QM, quantum field theory and quantum gravity.

Evidently, if (a version of) RQM were to present all of the above features, it would be a leading contestant in the arena of interpretations. The expectations are high, let us see how Rovelli intends to meet them.

2.2 The basic framework of RQM

Here I will focus on offering a clean outline of the uncontroversial framework of RQM and I will leave for later sections a discussion of the interpretation of ambiguous claims in the primary literature. I will use footnotes to reference the primary literature, as well as to quash any doubts that my presentation is not faithful to the primary literature.

2.2.1 The ontology of RQM:

The world as described by RQM is constituted by two basic elements: *systems* and *events*.[3] RQM assumes the possibility of analysing the world into systems (in many different ways), each system being characterised by an algebra of physical quantities.[4] *Whenever* two systems interact, and *only when*[5] they

[3]See, for instance, Rovelli (2022, p.1057). It is worth noting that Adlam and Rovelli (2023) claim that, at a fundamental level, the ontology of RQM consists exclusively of events, while systems should be understood as emergent from events. However, since I do not address questions of *fundamental* ontology, I will freely talk of systems as part of the ontology.

[4]See Adlam and Rovelli (2023, p.12), Rovelli (2021, p.1).

[5]'values have variables only during quantum events.' (Adlam and Rovelli, 2023, p.11).

interact, one or more of the quantities of each of the interacting systems takes on a value. A system's quantity taking on a value at an interaction is called an '*event*'. Interestingly, at all other times, quantities of systems do not have determinate values.[6]

What stands at the core of RQM is the claim that *events are relative* to the systems involved in the interaction. The scope of the relativity as well as the exact sense in which events are relative has been subject of development.[7] For the time being, it is sufficient to note two possibilities regarding the *scope* of the relativity. One possibility is that it is only the *values* taken at an interaction which are relative, whilst the fact that there is an interaction in which certain variables have taken on relative values is not relative, rather it is absolute.[8] Under this view, whenever two systems F and S interact, a quantity $\mathcal{V}$ of S takes a value v *relative to* F and a quantity $\mathcal{V}'$ of F takes a value v' *relative to* S.[9] Although I do intend to take a position on the *exact* meaning of the relativity involved in RQM, one thing may be noted: for a (conscious) agent to have a first-person experience consisting in a quantity having taken a value, the quantity must have taken a value relative to the agent. I will denote an interaction between two systems S and F with $S - F$ and I will denote an event in which S's quantity $\mathcal{V}$ takes a certain value relative to F as $e_S^{(F)}(\mathcal{V})$ and, if the specification of the value v taken by $\mathcal{V}$ is needed, I will use $e_S^{(F)}(\mathcal{V} = v)$.

[6] See, for instance, Adlam and Rovelli (2023, p.11-12), Rovelli (2022, p.1066).

[7] Adlam and Rovelli (2023) radically deflate the relativity of events, as compared to previous papers.

[8] This option is explicitly chosen by Adlam and Rovelli (2023).

[9] 'a quantum event arises in an interaction between two systems in which the variables of one system take on definite values relative to the other, *and vice versa*.' (Adlam and Rovelli, 2023, p.11, emphasis mine).

However, depending on one's understanding of interactions and events, one might also allow for the possibility of the occurrence itself of an interaction and thus the occurrence itself of events, to be relative. Under such an interpretation, interactions and events involve a double layer of relativity: whenever, *relative to a system* W, an interaction between F and S occurs, *relative to* W a quantity $\mathcal{V}$ of S takes a value v *relative to* F and, *relative to* W, a quantity $\mathcal{V}'$ of F takes a value v' *relative to* S. Hence, the occurrence itself of events $e_S^{(F)}(\mathcal{V})$ and $e_F^{(S)}(\mathcal{V}')$ is relative to a system W.[10] For a (conscious) agent to have a first-person experience consisting in a quantity having taken a value, the quantity must have taken a value relative to the agent in an event which occurred relative to the agent. When this second layer of relativity is at play, I will denote an interaction between two systems S and F which occurs relative to W as $[S - F]^W$ and an event in which, relative to W, S's quantity $\mathcal{V}$ takes a certain value relative to F as $[e_S^{(F)}(\mathcal{V})]^W$ and, if the specification of the value v taken by $\mathcal{V}$ is needed, I will use $[e_S^{(F)}(\mathcal{V} = v)]^W$.

Adjudicating which is the best interpretation of the relativity (or asboluteness) of interactions is not a straightforward question. A deep dive into the problems of defining interactions and events in RQM is required. Therefore, for the time being my exposition will proceed in a manner compatible with both approaches, by using parentheses to specify the eventual second layer of relativisation.

It is worth remarking that, under both interpretations, at any interaction

[10] This second interpretation is supported by many passages in the primary literature. For instance: 'the fact that a certain quantity q has taken a value with respect to O is a physical fact; as a physical fact, its being true, or not true, must be understood as relative to an observer, say P.' (Rovelli, 1997, p.8). See also Smerlak and Rovelli (2007, p.419) and Rovelli (2018, p.9).

between two systems F and S (relative to a system W) two events occur: $[e_S^{(F)}(\mathcal{V} = v)]^W$ and $[e_F^{(S)}(\mathcal{V}' = v')]^W$. Moreover, note that systems do not enter into events symmetrically, since an event *involves* one system but it is *relative to* another system: $[e_S^{(F)}(\mathcal{V} = v)]^W$ does not imply $[e_F^{(S)}(\mathcal{V} = v)]^W$.

Now that the basic ontology of RQM has been laid out, it's time to see how the formalism of quantum theory relates to such an ontology.

2.2.2 Quantum theory:

According to RQM, the formalism of quantum theory serves to offer probabilistic predictions regarding the occurrence of events and it is applied as follows.

An algebra of operators is assigned to each system, which represent the physical quantities of the system and whose eigenvalues define the possible values that the quantities may take.[11] Moreover, systems are assigned quantum states *relative to other systems*: given the set of events (relative to a system F), a system S may be assigned a quantum state relative to F, provided that there are events of the right kind in which a quantity of S has taken a value relative to F (relative to F). This condition will be further specified below. From the relativity of events it follows straightforwardly that quantum states are also relative and, in general, one system will have different quantum states relative to different systems. I will denote the quantum state of a system S relative to a system F as $|\psi\rangle_S^{(F)}$. Crucially, quantum states are not assigned relative to conscious observers only, rather they are assigned relative to any system, thus, in accordance with the goals stated at

[11] Rovelli (2022, p.1062).

the beginning of the section, no special role is assigned to agents.

Rovelli goes to pains to express that the *quantum state does not represent* the system or the world, rather it is only a useful mathematical tool which allows one to extract probabilities from a collection of relative events.[12] More precisely, we may say that, in RQM, the quantum state is not taken to represent the categorical, occurrent properties of a system, although, it may well encode some modal properties of the system it is assigned to, concerning probabilities of events involving the system itself (see the Relative Born Rule below).

To define the evolution of the quantum state, a Hamiltonian needs to be provided. The status of the Hamiltonian in RQM is a complex matter, which I will address in Chapter 5. For now, I will note that the evolution of the quantum state follows two rules. Consider two systems S and W such that S has a pure quantum state $|\psi(t)\rangle_S^{(W)}$ relative to W. $|\psi(t)\rangle_S^{(W)}$ evolves unitarily according to the Hamiltonian as long as S and W do not interact (relative to W).[13] On the other hand, at any interaction resulting in an event $[e_S^{(W)}(\mathcal{V} = v)]^W$, the relative quantum state collapses to the relevant eigenstate $|\psi\rangle_S^{(W)} \rightarrow \frac{\Pi_v|\psi\rangle_S^{(W)}}{|\Pi_v|\psi\rangle_S^{(W)}|}$, where Π_v is the projector associated with the value v of the quantity $\mathcal{V}$.[14] An example might be instructive.

Suppose S is a spin-$\frac{1}{2}$ system and suppose that in the last interaction with W (relative to W), the spin of S took the value $\frac{\hbar}{2}$ along the z axis relative to W (relative to W). Right after that interaction the quantum

[12]See Rovelli (2018).

[13]Rovelli (2021, p.5).

[14]'[T]here is collapse in each observer-dependent evolution of probabilities.' (Rovelli, 1996, p.1672). See also, Di Biagio and Rovelli (2022, p.5).

state of S relative to W is $|\psi(t_0)\rangle_S^{(W)} = |+z\rangle$. Suppose that the Hamiltonian governing $|\psi(t)\rangle_S^{(W)}$ after such an interaction gives rise to a unitary U. Then the quantum state of S relative to W evolves to $|\psi(t_1)\rangle_S^{(W)} = U\,|+z\rangle$. If W and S were to interact again (relative to W) and S's spin was to take a value relative to W, then the quantum state of S relative to W would collapse accordingly.

It's worth noting that the rule implies a collapse of an entangled joint quantum state in case of an interaction involving one of its subsystems. More precisely, suppose that S does not have a pure quantum state relative to W, because it is entangled with another system F. Suppose instead that $S \cup F$ has a quantum state $|\psi(t)\rangle_{S\cup F}^{(W)}$ relative to W. Then, at any interaction resulting in an event $[e_S^{(W)}(\mathcal{V} = v)]^W$, the joint relative quantum state collapses accordingly $|\psi\rangle_{S\cup F}^{(W)} \to \frac{\Pi_v|\psi\rangle_{S\cup F}^{(W)}}{|\Pi_v|\psi\rangle_{S\cup F}^{(W)}|}$.

These rules for the evolution of the quantum state indicate that systems do not necessarily have a quantum state relative to all systems. A system S has a quantum state relative to a system F, only if *either* there has been an interaction $[S - F]^F$ resulting in an event $[e_S^{(F)}(\mathcal{V} = v)]^F$, such that the value v singles out a unique eigenvector in the Hilbert space of S, *or* if there has been an interaction $[R - F]^F$ resulting in an event $[e_R^{(F)}(\mathcal{Q} = q)]^F$, such that q singles out a unique eigenvector in the Hilbert space of R and S is a subsystem of R.[15] Since events always involve *two distinct* interacting systems, one of which the event is relative to, while the other takes on a value of a certain

[15]In the latter case, S's quantum state relative to F may well be impure.

variable,[16] *there is no self- assignment of quantum states.*[17] Moreover, it may well be that a system does not have a quantum state relative to another system, because there is no requirement for all systems to have interacted with all other systems in the past. Nonetheless, I will assume that all systems do have a quantum state relative to *other distinct* systems, since it will be a useful simplifying assumption in the discussion below.

As mentioned above, quantum states are mathematical devices used to derive probabilities of the outcomes of interactions. Probabilities in RQM are derived according to the standard Born Rule,[18] with the important caveat that quantum states are relative in RQM:

Relative Born Rule: *At an interaction (relative to F) between two systems F and S (i.e. $[F - S]^F$), the probability relative to F for a quantity $\mathcal{V}$ of a system S to take on the value v relative to F is given by Born Rule on the*

[16]This is confirmed in the primary literature. For instance: 'A quantum event arises in an interaction between two systems such that the values of some physical variables of one system become definite relative to another system' (Adlam and Rovelli, 2023, p.2) and '[Events] are realized *only* at the interaction between (any) two physical systems' (Rovelli, 2018, p.1057).

[17]'the point of view presented here can then be characterized by a fundamental assumption prohibiting an observer to be able to give a full description of "itself."' (Rovelli, 1996, p.1672). The rejection of self-ascription is implied in the following inference by Adlam and Rovelli: there is no quantum state of the universe because 'quantum states are by definition relational, and there is nothing for the quantum state of the whole universe to be relativized to' (Adlam and Rovelli, 2023, p.12). See also Rovelli (2021, pp.4-5).

[18]It may not be perfectly transparent that Rovelli endorses the Relative Born Rule, but it is implied in different places. For example, consider the following paragraph:

> 'The theory [RQM] provides transition amplitudes of the form $W(b, a)$ that the determine the probability $P(b, a) = |W(b, a)|^2$ for a fact (or a collection of facts) b to occur, given that a fact (or a collection of facts) a has occurred. [...] An example of a transition probability is the probability $P(L_\phi = \hbar/2, L_z = \hbar/2) = \cos^2(\phi/2)$ of having spin $\hbar/2$ in a direction at angle ϕ from the z-axis (a fact) if the spin in the direction z was $\hbar/2$ (a fact).' Rovelli (2022, pp. 1057-8)

Other confirming paragraphs in the primary literature may be found, for example, in Adlam and Rovelli (2023, p.11-) and Di Biagio and Rovelli (2021, p.30).

quantum state of S relative to F.

It's worth noting that from the relativity of quantum states it follows that probabilities in RQM are also relative to systems.

Thus far, I have laid out the basic and uncontroversial elements of the framework of RQM. However, the attentive reader will note a gaping hole in the account. Given an interaction where a quantity $\mathcal{V}$ of a system F obtains a definite value relative to the system S, we now know how to use the quantum state to derive the probabilities for the possible values of such a quantity. However, it is not yet clear how the theory predicts the circumstances in which interactions occur and which event occurs (i.e. what quantity becomes determinate) in each interaction. The search for a resolution of this issue will occupy most of the rest of this thesis.

However, before moving onto a discussion on interactions, I will present a condition on quantum states, which is part of the core, uncontroversial set-up of RQM.

2.3 The 'consistency condition'

2.3.1 Internal Consistency

Since the inception of RQM, Rovelli imposed a powerful 'consistency condition' (Rovelli, 1996, p.1652) on the assignment of quantum states relative to different systems. Roughly speaking, the condition imposes that whenever an interaction between two systems F and S results in quantities $\mathcal{V}$ and $\mathcal{V}'$ taking value relative to, respectively, F and S, all quantum states $|\psi\rangle^{(W)}_{F\cup S}$ of

$F \cup S$ relative to a third system W, must predict the same perfect correlation between the quantities $\mathcal{V}$ and $\mathcal{V}'$. More precisely:

Internal Consistency: *Whenever an interaction $[F-S]^F$ between two systems F and S resulting in events $[e_S^{(F)}(\mathcal{V})]^F$ and $[e_F^{(S)}(\mathcal{V}')]^F$ occurs (relative to F), all of the quantum states of $S \cup F$ relative to third systems (W), predict a perfect correlation between the same values of variables $\mathcal{V}$ and $\mathcal{V}'$.*

where the following is meant by a 'perfect correlation between the same values of variables $\mathcal{V}$ and $\mathcal{V}'$. Suppose the variables $\mathcal{V}$ and $\mathcal{V}'$ are associated with the bases $\{|v_i\rangle\}$ and $\{|v_i'\rangle\}$. Suppose that the quantum state of $S \cup F$ relative to W is a pure quantum state $|\psi\rangle_{S\cup F}^{(W)}$. Then there is a perfect correlation between the values associated with $\{|v_i\rangle\}$ and $\{|v_i'\rangle\}$ if and only if the quantum state has the Schmidt basis $\{|v_i\rangle \otimes |v_i'\rangle\}$:

$$|\psi\rangle_{S\cup F}^{(W)} = \sum_i \alpha_i |v_i, v_i'\rangle$$

where $\alpha_i \in \mathbb{C}, \Sigma_i |\alpha_i|^2 = 1$. If the quantum state of $S \cup F$ relative to W is the impure quantum state $\rho_{S\cup F}^{(W)}$, then it predicts a perfect correlation between the values associated with $\{|v_i\rangle\}$ and $\{|v_i'\rangle\}$ if and only if:

$$\forall i \neq j \ \mathrm{Tr}(\rho_{S\cup F}^{(W)} |v_i, v_j'\rangle \langle v_i, v_j'|) = 0.$$

For simplicity, I will only focus on the case of observables with discrete spectra. It may be that the case of continuous spectra causes more complications for RQM. I will set aside such difficulties for the puroposes of this thesis.

The condition that I have formalised above has appeared in different versions across the primary literature (or better, many closely related statements have appeared across the primary literature). It was discussed at length in Rovelli (1996, pp.1650-1652) and Rovelli (1997, pp. 7-9) and it appeared in Di Biagio and Rovelli (2022) and Adlam and Rovelli (2023) as postulate (6), quoted below. However, in no writing it has appeared in the form I give above. Therefore, I will spend a few words justifying why I believe my formulation is faithful to the primary literature, other than being the clearest formulation.

In Adlam and Rovelli (2023, p3) the condition is stated as follows:

Postulate (6): *In a scenario where F measures S, and W also measures S in the same basis, and W then interacts with F to "check the reading" of a pointer variable (i.e., by measuring F in the appropriate "pointer basis"), the two values found are in agreement. (Adlam and Rovelli, 2023, p.3, notation adapted to fit mine)*

There is a sense in which Postulate (6) is stronger than Internal Consistency. Postulate (6) does not require only a perfect correlation in the outcomes of the measurements performed by W on F and S, but it also requires that they '*agree*': the outcomes of W's interactions with S and F must be such that the pointer variable on F relative to W is in agreement with the outcome obtained on S relative to W. An example might make it clearer. Suppose that F and W measure S's spin in the z direction and suppose that S's spin-z takes a value *up* relative to W in the measurement performed by W. Then postulate (6) requires that the outcome of the measurement by W on F's pointer value must agree with the outcome of W's measurement on S, namely it has to result in a pointer value interpreted as *up*. In other words, Postulate (6) requires a correlation of 1 between *specific pairings* of v_i and v'_j. Instead, Internal Consistency only guarantees that all systems will find a correlation of 1 between the same pairings of v_i and v'_j, but the pairings are not specified and thus they are not required to "agree". For the time being, I will ignore the stronger requirement of agreement.

A more pressing problem is instead the use of the word 'measurement' in Postulate (6), rather than the words 'interaction' or 'event'. The primary literature draws a distinction between measurements and interactions, specifically, a measurement involves not only an interaction between two systems, but also decohering interactions between one of the systems (the apparatus) and the environment.[19] Therefore, from formulations such as the above, some readers might be convinced that, really, the consistency requirement is intended to apply to measurements only, rather than to all interactions. Establishing whether the consistency condition refers to interactions or measurements is crucial.

Thankfully, many claims across the primary literature show that, instead, the condition is about interactions and events in general: '(i) a variable of S has a value with respect to F and (ii) with respect to W, there is a correlation to be expected between a variable of S and a pointer variable of F [according to $|\psi\rangle^{(W)}_{S\cup F}$]. The first implies the second' (Di Biagio and Rovelli, 2022, p.8). Another example of a statement confirming this interpretation may be found in Rovelli (1996, p.1654): 'the fact that q has a value relative to O means that q is correlated with the pointer variable in O. [...] By "O has information

[19] For more detail this, see Di Biagio and Rovelli (2021, p.5-6).

about q" we mean "relative to O, q has a value" and also "relative to P, there is a certain correlation in the S and O states."' There is no mention of measurement in either of these claims, rather there is only a mention of a variable taking a value. Thus, we are led to formulate Internal Consistency as referring to interactions in general.

My formulation also differs from others in the primary literature in accounting for the possibility that the occurrence itself of an event is relative. In the claim by Di Biagio and Rovelli quoted above, they speak of the event of a variable of S taking a value relative to a system F without any mention of *relative to which system* the event takes place. Similarly, in Adlam and Rovelli's passage quoted above, they refer to a 'scenario' in which certain measurements (and thus events) occur, without specifying what system they are relative to. However, as noted above, according to certain versions of RQM the occurrence of events is relative, thus it is appropriate to account for such a possibility.

It is not straightforward to decide how to add this second layer of relativity, since the formulations in the primary literature simply ignore this factor. As displayed in my formulation above, I claim that the antecedent of the conditional should be taken as referring to events occurring relative to one of the systems involved in the events, for instance, whenever $[e_S^{(F)}(\mathcal{V})]^F$ and $[e_F^{(S)}(\mathcal{V}')]^F$ occur.

An analysis of how the consistency condition has been used in the primary literature quickly reveals that my interpretation is correct. First, note that the consistency condition is introduced by Rovelli (1996) in the attempt to bridge the perspective of a system involved in an interaction with the perspective of third systems not involved in the interaction. Rovelli (1996) appeals to the consistency condition to tackle 'the problem of the relation between distinct descriptions of the same events' because '[w]e do not like a solipsistic world of uncommunicative observers, nor, in any case, is this what quantum mechanics describes.' (*ibid*, p.1650-1). He then proceeds to derive and describe the relation between the quantum theoretic descriptions of an event from the perspective of a system directly involved in the interaction, and a third system. Hence, were the occurrence of events to be relative, the disambiguation I provided above is most faithful the primary literature: roughly, if an interaction involving F and S occurs relative to F, then the quantum state of $F \cup S$ relative to a third system W must display the appropriate correlations.

Further evidence of my interpretation can be found in Adlam and Rovelli (2022, p.5). They use the consistency condition to relate an experimental outcome that Alice 'witnesses' on a system S and the experimental outcomes that Bob obtains on Alice and S. Given the verb 'witness', it's clear that the experimental outcome is taken to be relative to Alice: thus whenever $[e_S^{(Alice)}(\mathcal{V})]^{Alice}$ and $[e_{Alice}^{(S)}(\mathcal{V}')]^{Alice}$ occur, then the quantum state $|\psi\rangle_{S\cup Alice}^{(Bob)}$ must display the appropriate correlations.

Finally, an attentive reader might note that Rovelli's original statements tend only to mention the correlations that would arise *in case* a third system were to interact appropriately with the systems involved in the original interaction, while I directly talk about the quantum state. I mention the quantum state to make explicit the constraint that this condition places on quantum states relative to third systems. My formulation is, however, still faithful to the primary literature, since, as I show below, Rovelli (1996) derives this consistency condition *from* the form of the quantum state relative to a third system.

Now that I have established the precise form of the Internal Consistency condition, I will move onto an analysis of its logical relationship to the framework of RQM, which will also offer an opportunity to present the motivating thought experiment behind RQM, namely the Wigner's friend scenario.

2.3.2 Wigner's friend and Internal Consistency

The previous section prompts a natural question concerning the logical relationship between Internal Consistency and the already stated basic framework of RQM: is Internal Consistency implied by the basic framework, or is it a further condition enforced upon the basic framework? The present section is focused on such a question.

Interestingly, Rovelli argues that it simply falls out of the basic framework of RQM (Rovelli, 1996, pp. 1650-2, 2019, section 2.6). Indeed, Rovelli (1996) first introduces (a condition similar to) Internal Consistency as a consequence of the analysis of the "Wigner's friend" scenario within RQM. Unfortunately, I will show here that Rovelli makes an unwarranted assumption in his derivation, and thus Internal Consistency does not fall out of the already stated framework of RQM. Rather, it is a powerful constraint imposed upon the basic framework of RQM.

The Wigner's friend scenario (Winger, 1961), also termed the "third-person problem" by Rovelli (1996), is a scenario in which the application of the standard rules of quantum mechanics leads to two observers correctly assigning different states to the same system. Coupled with certain intuitive, (possibly naïve) assumptions about the status of the quantum state, the differing assignments of quantum states lead to some puzzling consequences.

I will closely follow Rovelli's (1996) presentation of the scenario. Consider a spin-$\frac{1}{2}$ system S, and two human observers, namely Wigner's friend F and Wigner W. Suppose Wigner's friend and the system S are in a laboratory isolated from Wigner and suppose F performs a spin measurement on S at a time t_2. Suppose that at a time t_1 before the measurement the quantum state of S is in a superposition of $|\uparrow\rangle$ and $|\downarrow\rangle$:

$$|\psi(t_1)\rangle_S = \alpha\,|\uparrow\rangle + \beta\,|\downarrow\rangle$$

with α and β non-zero. Finally, suppose that F's experiment on S results in $|\uparrow\rangle$. Then F will describe the situation as follows:

$$|\psi(t_1)\rangle_S = \alpha\,|\uparrow\rangle + \beta\,|\downarrow\rangle \rightarrow |\psi(t_2)\rangle_S = |\uparrow\rangle$$

according to orthodox quantum mechanics.

According to orthodox quantum mechanics, Wigner's quantum theoretic account of the situation differs. The quantum states of S and F at the time t_1 are:

$$|\psi(t_1)\rangle_S = \alpha\,|\uparrow\rangle + \beta\,|\downarrow\rangle \tag{2.1}$$

$$|\psi(t_1)\rangle_F = |init\rangle \tag{2.2}$$

Suppose Wigner does not perform a measurement on S, F or $S \cup F$ between the times t_1 and t_2. Then he will describe the situation unitarily. According to a standard unitary account of a measurement process (Von Neumann, 1932), the quantum state of S becomes entangled with the quantum state of Wigner's friend F as follows:

$$|\psi(t_1)\rangle_{S \cup F} = (\alpha\,|{\uparrow}\rangle + \beta\,|{\downarrow}\rangle) \otimes |init\rangle \rightarrow |\psi(t_2)\rangle_{S \cup F} = (\alpha\,|{\uparrow}\rangle \otimes |F_{\uparrow}\rangle + \beta\,|{\downarrow}\rangle \otimes |F_{\downarrow}\rangle)$$

where $|F_{\uparrow}\rangle$ and $|F_{\downarrow}\rangle$ correspond to F witnessing, respectively, the up and down outcomes. Thus, although both F and W applied the standard rules of quantum theory correctly, the quantum description of the situation relative to Wigner differs from that of his friend.

Under certain assumptions about the relation between the quantum state of a system and the system itself, apparently puzzling consequences follow. For instance, if one assumes the eigenstate-eigenvalue link, namely the claim that an observable takes a determinate value on a system if and only if the system is in an eigenstate of that value, then one concludes that from the perspective of Wigner's friend, the spin of S has a determinate value, but it does not have such a determinate value from the perspective of Wigner. In general, if one assumes that the quantum state represents the physical state of the system it is assigned to, then, *at least prima facie*, it would seem that S has two different physical states relative to F and W.

It is immediately evident why Rovelli takes the Wigner's friend scenario as motivating RQM. Essentially, RQM's dissolution of the the puzzles suggested by the Wigner's friend scenario is that there are no puzzles: the values of physical variables *just are* relative to systems. When (relative to F) Wigner's friend F interacts with S, S's spin takes a value relative to F (relative to F). The ontology of RQM ensures that S's spin taking a value relative to F (relative to F) does not imply it taking a value relative to any other system (relative to any system). This relativity of values is not a problem, rather it is simply how the world is. Analogously, there is no problem with assigning different quantum states to the same system S from the perspective of two distinct systems F and W.

Moreover, Rovelli does not only use the the Wigner's friend scenario as a motivation for RQM. He also appeals to it in order to derive Internal Consistency. Rovelli (1996, 1997) and Laudisa and Rovelli (2019) claim that it 'follows directly from quantum theory' (Laudisa and Rovelli, 2019, section 2.6) that after the interaction $[S-F]^F$ in which S's spin-z becomes determinate, the quantum state of $S \cup F$ relative to a third system W will display a perfect correlation between the spin-z states of S and the corresponding pointer states of F. Rovelli's position is summed up well in Laudisa and Rovelli (*ibid*, notation adapted to mine):

> Suppose the variable $[v]$ of $[S]$ is measured by $[F]$ and stored into the variable $[v']$ of $[F]$. This means that the interaction has created a correlation between $[v]$ and $[v']$. In turn, this means that a third system measuring $[v]$ and $[v']$ will certainly find consistent values.

Thus Laudisa and Rovelli suggest that Internal Consistency holds 'because quantum theory predicts so'(*ibid*). Unfortunately, within RQM it is not the case that quantum theory implies Internal Consistency.

The conclusion that the final quantum state relative to Wigner displays a perfect correlation between the spin-z variables of S and the pointer variables of F relies on the assumption that the quantum state relative to Wigner of $S \cup F$ at the time t_1 before the experiment is:

$$|\psi(t_1)\rangle^{(W)}_{S\cup F} = (\alpha\,|\uparrow\rangle + \beta\,|\downarrow\rangle) \otimes |init\rangle$$

and that it evolves as described above. However, in RQM we have no reason to believe that the quantum state relative to Wigner must take such a form and, more importantly, we have no reason to believe that the quantum state relative to *all* third systems will take such a form.[20] In fact, as noted above, the quantum state of $S \cup F$ depends on which quantum events occurred (relative to W) in which a variable of S, F or $S \cup F$ took a value relative to W and which values obtained. The basic framework of RQM does not enforce any agreement between events relative to different systems. Consequently, the basic framework does not provide any reason for the claim that the quantum state of $S \cup F$ relative to any third system will take the form given above at time t_1.

Therefore, contrary to what Rovelli suggests, Internal Consistency does not follow from the basic framework of RQM outlined in Section 2.2 of the present chapter. Instead, it should be conceived as a powerful assumption imposed over and above the basic framework which constraints the assign-

[20] I will also argue in Chapter 5 that we might have no reason to believe that it evolves as described above relative to all systems, because of the relativity of the Hamiltonian. However, for the purpose at hand, noting the relativity of quantum states is sufficient.

ments of relative quantum states, and thus, in turn, which relative events occur and their outcomes.

Chapter 3

Events, interactions and the problem of measurement

In the present chapter, I argue that RQM needs to provide a specification of the circumstances in which interactions occur in RQM and which variables are determined in each interaction. In particular, I argue that such a specification needs to meet two requirements. Firstly, it must unambiguously predict the occurrence of the interactions that are relevant in the explanation of all successful quantum mechanical predictions as well as predicting which variable becomes determinate in each such interaction. Secondly, it must motivate the claim that interactions occur relative to all systems, also outside of experimental situations.

I will start by contextualising my arguments within the broader discussion on the measurement problem in quantum mechanics. In particular, I will note that my requirement for a specification of the circumstances in which an interaction occurs is a well-known facet of the measurement problem, in the version most famously presented by Bell (1990). I will also briefly rebut some claims by Oldofredi (2023) concerning how RQM allegedly "dissolves" the measurement problem. I will then move on to providing my own arguments for the requirement of a specification of the circumstances in which interactions occur, starting from the uncontroversial premiss that RQM needs to recover the usual, successful quantum mechanical predictions. I will argue that such a specification must meet the two requirements stated above, but it need not specify the exact time of an interaction and it need not be a reductive definition of interaction, although it cannot appeal to notions such as measurements, agents or classical/quantum divide.

Just as in Chapter 1, I will be neutral on whether the occurrence of events itself is relative. My notation will display this second layer of relativity, which can simply be ignored in case the occurrence of events and interactions is taken not to be relative.

3.1 Bell's measurement problem:

My requirement for a specification of the circumstances for the occurrences of interactions is just one of the many faces of the problem of measurement and it is nothing new. This same problem was formulated most famously by Bell (1990), among many others, who argued that orthodox quantum theory lacks a precise determination of the circumstances in which the unitary dynamics of the quantum state stops applying and, instead, the collapse dynamics does. Bell argues that such a precise determination should not rely on a "shifty split" between the classical and the quantum or any concepts such as measurement. While interpretations which only appeal to unitary dynamics avoid this sort of problem, RQM does not, since it appeals to both kinds of dynamics. In the context of RQM, asking for a precise specification of when unitary dynamics breaks down simply amounts to asking for a precise specification of when interactions occur.

In a recent discussion on how quantum theory "dissolves" the measurement problem, Oldofredi (2023) argues that, in the context of RQM, the collapse postulate 'does not cause additional interpretational troubles' (*ibid.* p.8). He explains that 'since in Rovelli's theory ψ is not considered a real object but rather a mere computational tool, nothing physical is literally collapsing in measurement interactions' (*ibid.* p.7). Instead, collapse is just 'an information update relative to a certain agent' (*ibid.* p.7). For these reasons he claims that in RQM 'the collapse postulate does not generate conceptual conundra' (*ibid.* p.7). Moreover, he argues that 'the exact details about the mechanisms causing the suspension of the unitary dynamics cannot be available in RQM' (*ibid.* p.7). This is just a limit of the descriptive capabilities of RQM, he explains, and it should not be considered a drawback. Thus, he concludes, the collapse postulate is not problematic in RQM.

However, the claim that the quantum state does not represent a concrete object (or occurrent categorical properties) does not resolve the (Bell's) measurement problem, at least on its own. Firstly, it's worth noting that collapse is not just 'an information update relative to a certain agent' (*ibid.* p.7) for the simple fact that quantum states hold relative to any system, not just agents. It's important to stress that the collapse of the quantum state does not represent an update in an agent's knowledge about a system, rather it represents a change in an *objective* relation between two systems.[1]

Moreover, even if the quantum state does not to represent a concrete object or occurrent categorical properties of an object, it does encode the probabilities for values of quantities in future relative events. Consequently, the evolution of relative quantum states, including the evolution via collapse, determines the evolution of relative probabilities for events relative to a system. Rovelli (2021, pp.1058-9) himself points out that the suppression of interference is one example of how collapse changes the probabilities encoded in the quantum state. Therefore, to make sure that RQM *unambiguously* predicts probabilities for events relative to a system, one needs a clear and unambiguous specification of the circumstances in which the collapse of the (relative) quantum state occurs, and the basis in which it occurs.

Prima facie, RQM offers such an unambiguous answer: as stated in Chapter 2 collapse of the quantum state of S relative to F in the basis corresponding to $\mathcal{V}$ occurs whenever an interaction $[F - S]^F$ resulting in an event $[e(\mathcal{V})_S^{(F)}]^F$ occurs. Evidently, this answer immediately calls for another question: what are the circumstances in which such an interaction occurs? If RQM is to resolve this version of the measurement problem, it needs to provide an answer to this question.

In what follows I will provide an argument for the requirement to provide such a specification of the circumstances in which interactions occur. With the argument at hand, I will also be able to define precisely the exact requisites for such a specifications as well as defining what needs not be specified.

[1] Since the quantum state is *objectively* determined by the occurrence of relative events.

3.2 The problem with predictions:

Any plausible interpretation of quantum mechanics must recover all of its successful predictions. I argue that in order for RQM to recover the successful predictions of quantum mechanics a specification of the circumstances in which interactions occur is necessary.

Consider an example of how RQM might be used to make predictions. Suppose a scientist F is performing a spin measurement on a system S, using a measuring apparatus A. Given all of the relevant information, the scientist should be able to use quantum theory to predict a set of possible outcomes of the experiment, one of which will obtain (at least relative to F), and the probabilities assigned to each outcome. Although, in practice, the scientist might appeal to vague notions such as measurement or a classical/quantum divide, RQM must be able to recover the scientist's predictions, without appeal to such notions, if RQM is to satisfy its own desiderata.

In the context of RQM's ontology of systems and events, an outcome of such an experiment involves, at the very least, the occurrence of an event $[e_A^{(F)}(X)]^F$, in which (relative to the scientist) a certain quantity of the apparatus (e.g. the position X of a pointer) takes a value relative to the scientist. Note that, if a second layer of relativity is at play, the occurrence of the interaction between the A and F must be relative to the scientist F, since RQM needs to predict that scientists will themselves have a first-person experience consisting in part of the outcome on the apparatus. One might also envisage that the account of a measurement of spin within RQM would involve other events as well, such as an event $[e_S^{(A)}(spin)]^F$, namely the spin of the particle

S taking a value relative to the apparatus A (relative to the scientist).[2] However, for the purposes of my argument, it suffices to note that the occurrence of $[e_A^{(F)}(X)]^F$ is a necessary part of the account of a measurement outcome within RQM.

Therefore, for RQM to recover the predictions of orthodox quantum mechanics, RQM must provide a way to predict the occurrence of an event of the form $[e_A^{(F)}(X)]^F$, given all the relevant information. Since events occur at interactions between systems, RQM must predict the occurrence of an interaction between the scientist and the apparatus (relative to the scientist), which results in such an event. In other words, RQM must identify some features of the physical circumstance/situation that the scientist finds themselves in and claim that such features ensure the occurrence of an interaction between the scientist and the apparatus.

Moreover, in each experimental situation, orthodox quantum theory predicts certain probabilities for each outcome. Therefore, in order for RQM to recover the predictions of orthodox quantum mechanics, RQM is also required to predict the correct probabilities for each event, at least to a level of approximation required to explain all verified applications of quantum theory. In other words, RQM needs to predict the correct probability for each $[e_A^{(F)}(X = x_i)]^F$, where x_i are the possible values of the variable X, to a sufficient level of approximation. This is done in RQM by ensuring a certain quantum state of A relative to F obtains. Given the evolution rules of quantum states in RQM, this will involve appropriate events between A, F and

[2]Indeed, Di Biagio and Rovelli's (2021, pp.5-6) account of measurement in RQM does involve such events.

possibly other systems (such as S) having occurred (relative to F) before the experiment (possibly at the preparation stage), and an appropriate evolution of the state $|\psi\rangle_A^{(F)}$. Note that the probabilities assigned by orthodox quantum theory to certain experimental outcomes may depend on particular settings of the preparation device, thus probabilities in RQM are also required to display such a dependence, expressed as a dependence between relative events.

In sum, RQM must provide a specification of the circumstances for the occurrence of interactions such that, in all succcesful applications of quantum theory, it unambiguously predicts the interactions relevant to the explanation of quantum mechanical predictions and appropriate probabilities for them. As I will argue in the next section, this is not all that is required of RQM.

3.3 A motivation for the ontology:

According to RQM, interactions occur in all kinds of situations and between all kinds of systems, not just in experimental situation. RQM needs to justify this claim.

I have argued that RQM justifies the prediction that an interaction occurs between the scientist and the apparatus because of some features of the physical situation of the scientist and apparatus holding. In order to justify the claim that interactions no different from the ones between the scientist and the apparatus also occur in all kinds of other situations and between all kinds of systems, the same or similar features which denote the occurrence of an interaction between the scientist and the apparatus must be identifiable in all kinds of situations involving all kinds of systems, at least in principle.

Therefore, the specification of the circumstances in which interactions occur is required to cover the occurrence of interactions in all kinds of situations involving all kinds of systems. However, note that, while in the case of experimental situations RQM is required to exactly predict the appropriate interactions which explain the quantum mechanical predictions, outside of experimental situations the requirements is more lax. RQM only needs to *justify* the claim that outside of experimental situations there are interactions like the ones between scientists and the apparatus. Such motivation is given by showing that the features which denote the occurrence of an interaction in experimental situations are also present in all other situations. But RQM is not under an obligation to *exactly predict* which interactions occur, when the physical situation is far from experimentally verifiable predictions. It may well be that, in such situations, RQM only offers approximate answers on which interactions occur.

In sum, RQM must motivate the claim that in the world there interactions (and thus events) between all kinds of systems.[3] RQM must also exactly predict the occurrence of certain such interactions, allowing for a great wealth of predictions and applications. However, it may be that RQM cannot manage to predict exactly the occurrence of *all* interactions, in all physical situations.

[3]Note that an appeal to some form of scientific realism will form part of the motivation.

3.4 Time and order of interactions:

I have argued that RQM needs to state the circumstances in which an interaction occurs and which variable is determined at each interaction. Healey (2022, pp.6-7) and Muciño et al. (2022, pp.10-11) are concerned more specifically with a need for RQM to specify an exact *time* at which each interaction takes place:

> '[RQM] needs for there to be a well-defined moment at which each interaction takes place; otherwise, the proposal becomes vague and loses all strength. (Muciño et al., 2022, p.10)

However, Adlam and Rovelli argue that 'RQM does not need to insist that events occur at well-defined spacetime locations' (Adlam and Rovelli, 2022, p.17), because one may hold that 'spacetime should be understood to emerge from a background of quantum events' (*ibid*).

Following Adlam and Rovelli's clarification, I will not demand that events have an exact spatio-temporal location. However, even if events do not have a well-defined, exact, time at which they occur, at the very least RQM has to recover some facts about the *order* of events in some situations. Consider a scientist performing multiple, successive spin experiments on one system in the following way. The experiment consists in a sequence of spin-measurement devices, such that, the outcome of the experiment in one of the devices determines which device the system will go through next. The experimenter will witness and note down each outcome one after another. Although RQM is not required to specify the exact time of each interaction between the scientist and apparatus (relative to the scientist), it is required to recover the order of them, as witnessed by the scientist.[4] As already argued, RQM needs to specify the circumstances of the occurrence of interactions, and which interactions occur in which circumstance, in such a way that experimental predictions are correctly explained. Sometimes, that involves predicting an order among the interactions.[5]

3.5 Concluding remarks

Hence, RQM is required to provide a specification of the circumstances for the occurrence of interactions and for which variable becomes determined in each interaction, such that, (i) in all experimental applications of quantum theory, it unambiguously predicts the interactions relevant to the explanation of quantum mechanical predictions in the appropriate order and with the appropriate probabilities and (ii) it justifies the claim that interactions occur between all kinds of systems and outside of experimental contexts. I call the challenge of offering such a specification RQM's measurement problem, given its clear relationship with standard formulations of the problem of measurement.

Before closing this section, it's worth making precise two aspects of this requirement. Firstly, this is not demand for a reductive definition of interaction in terms of other concepts or notions. It should be open to RQM

[4]Note that for the purposes of this thesis, I do not require that the order is *fundamentally directed*, thus what Adlam (2023) calls a bi-order is sufficient.

[5]Rovelli (1996, p.1652, 1997, pp. 8-9) as well as Adlam and Rovelli (2022, p.18) suggest that the exact time of an event might be defined relatively and probabilistically. However, in this thesis, I consider these suggestions only briefly (Chapter 4, footnotes 1, 3) because, before adding this extra layer of complexity, I need to deal with the more pressing problem of understanding how the occurrence of interactions is indicated by the theory.

to claim that interaction is a primitive notion, although, obviously, such a claim neither provides the specification that is required nor denies the need for it. Secondly, in accordance with the aims listed as number (1) and (2) in Section 2.1, RQM cannot appeal to primitive notions of measurements, agents, minds nor to a classical/quantum divide in order to provide such a specification. In light of this, it would appear that the most natural place to look for a specification of the circumstances in which an interaction occurs is the quantum formalism itself. Indeed, as I will show in the next sections, this is where the proposals by Rovelli and his collaborators head towards.

Chapter 4

Interactions as correlations

In Rovelli's early writings on RQM (Rovelli 1996, 1997) there are strong suggestions that interactions just are the establishment of correlations. In the present chapter I will explore such an intuition of "interactions as correlations" in depth and evaluate whether there is a plausible and coherent way of making the intuition precise in such a way that the requirements set out in Chapter 3 are met.

I will start by introducing the textual evidence for the "interactions as correlations" intuition before I proceed to analyse three natural ways of cashing out the intuition into a well-defined principle. I analyse each principle one at a time, and the criticism of one principle will motivate the exploration of the successive principle or, finally, the abandonment of the "interactions as correlations" intuition.

Although the suggestion that interactions are just correlations has been recently disavowed by Di Biagio and Rovelli (2022), it is still worth exploring it in depth for two reasons. Firstly, the exploration of this possibility clarifies what other avenues are available to RQM and why. Secondly, since other alternative are also plagued by severe problems, it is worth ensuring that the "interaction as correlations" conception is not an available option.

4.1 The "interactions as correlations" intuition

In the early writings by Rovelli on RQM, he suggests that events occurring between two systems are indicated by correlations in the quantum state of such systems relative to a third system. Statements like the following abound:

> 'From the point of view of the [W] description: *The fact that the pointer variable in [F] has information about [S] (has measured [v]) is expressed by the existence of a correlation between the [v] variable of [S] and the pointer variable of [F]. The existence of this correlation is a measurable property of the [F − S] state.*' (Rovelli, 1996, p.1652, emphasis in original, notation adapted to mine)

and:

> I will denote the relation between a physical quantity [v] of a system [S] and the observer system [F] with respect to which q has a certain value as "information." I will say "[F] has the information that [v] = 1" to mean "[v] = 1 relative to [S]." [...] it should be possible to understand what is the physical meaning of "[v] has a value relative to [F]" by considering the description

that $[W]$ gives (or could give) of the $[S-F]$ system. (Rovelli, 1996, p.1653, notation adapted to mine)

'By "$[F]$ has information about $[v]$" we mean "relative to $[F]$, $[v]$ has a value" and also "relative to $[W]$, there is a certain correlation in the S and $[F]$ states."'(Rovelli, 1996, p.1654, notation adapted to mine)

Evidently, the Internal Consistency condition introduced in Chapter 2 is closely related to these suggestions. Indeed, Internal Consistency ensures that a correlation between variables of S and F in the quantum state $|\psi\rangle^{(W)}_{S\cup F}$ of $S\cup F$ relative to W is a *necessary condition* for an interaction in which such variables take a value relative to the other system. However, the above quotes seem to suggest more than Internal Consistency. They seem to indicate a necessary *and sufficient* link between correlations in the quantum state $|\psi\rangle^{(W)}_{S\cup F}$ and interactions between S and F. In what follows I will explore how one might try to cash out such a link into a precisely stated condition.

4.2 Interactions as Relative Correlations

The following is one natural way of making precise the mooted necessary and sufficient link between the occurrence of an interaction between two systems and a correlation in the quantum state of the two systems relative to a third system:

Interactions as Relative Correlations: *For any two distinct systems F, S and a system W (possibly identical to F or S) a pair of events $[e^{(F)}_S(\mathcal{V})]^W$ and*

$[e_F^{(S)}(\mathcal{V}')]^W$ *occur at a time* t *if and only if there is a quantum state* $|\psi(t)\rangle_{S\cup F}^{(W)}$ *or* $\rho(t)_{S\cup F}^{(W)}$ *of* $S \cup F$ *relative to* W *and such a quantum state predicts a perfect correlation between values of* $\mathcal{V}$ *and* $\mathcal{V}'$*.*

In more mathematical terms, $[e_S^{(F)}(\mathcal{V})]^W$ and $[e_F^{(S)}(\mathcal{V}')]^W$ occur at a time t if and only if *either* there is a pure quantum state $|\psi\rangle_{S\cup F}^{(W)}$ which may be expressed as a Schmidt decomposition:

$$|\psi\rangle_{S\cup S}^{(W)} = \sum_i \alpha_i |v_i\rangle \otimes |v_i'\rangle$$

where $\sum_i |\alpha_i|^2 = 1$, *or* there is an impure quantum state $\rho_{S\cup F}^{(W)}$ such that:

$$\forall i \neq j \ \mathrm{Tr}(\rho_{S\cup F}^{(W)} |v_i, v_j'\rangle \langle v_i, v_j'|) = 0$$

where $\{|v_i\rangle\}$ and $\{|v_i'\rangle\}$ are the bases corresponding to $\mathcal{V}$ and $\mathcal{V}'$.[1] Following convention, I will call the α_i Schmidt coefficients and the $\{|v_i, v_i'\rangle\}$ the Schmidt basis. As in Chapter 2, for simplicity, I will only focus on the case of observables with discrete spectra.

Interactions as Relative Correlations determines the circumstances in which an interaction occurs relative to a system W, thus, prima facie, RQM with Interactions as Relative Correlations is a candidate to meet the requirements set out in Chapter 3.

[1]One may be inspired by Rovelli (1996, p.1652, 1997, pp.8-9) to consider a principle similar to Interactions as Relative Correlations, according to which the Born probability relative to W of finding perfect correlations in the variables $\mathcal{V}$ and $\mathcal{V}'$ of, respectively, S and F defines the probability relative to W that events $[e_S^{(F)}(\mathcal{V})]^W$ and $[e_F^{(S)}(\mathcal{V}')]^W$ have occurred. I won't consider this probabilistic principle, as it adds further complications, and, as it will become apparent below, it suffers from the same problem as Interactions as Relative Correlations, thus it may be discarded with Interactions as Relative Correlations.

It's worth noting some features of Interactions as Relative Correlations. First, it not only defines an order in the interactions, but it exactly defines the time at which an interaction occurs, going beyond what I claim is required of RQM. Secondly, Interactions as Relative Correlations also determines *what variable* takes a value in each interaction (the ones which are correlated) and thus also determines *which* interaction occurs, even though, due to the non-uniqueness of the Schmidt decomposition, it might not select a unique variable (see Section 4.4 below). For the moment, I will set aside the problem of non-uniqueness of the selected variables.

Thirdly, since Interactions as Relative Correlations relies on the *relative* quantum state to denote the occurrence of an interaction, the occurrence of the interaction itself is relative. If, in general, quantum states relative to different systems are different, then they will also predict different correlations. Hence, relative to different systems, there will be different interactions going on. The formulation of the principle itself makes it clear, since it refers to events $[e_S^{(F)}(\mathcal{V})]^W$ and $[e_F^{(S)}(\mathcal{V}')]^W$, namely events occurring *relative to a system* W, rather than events occurring simpliciter.

Nonetheless, unfortunately Interactions as Relative Correlations does not fulfil the requirements set out in Chapter 3, at least on its own, because, for any systems S and F, it fails to predict the occurrence of events of the form $[e_S^{(F)}(\mathcal{V})]^F$. The reason is the following.

According to Interactions as Relative Correlations an interaction involving two system S and F occurs relative to a system W if and only if there is a quantum state of $S \cup F$ relative to W which perfectly correlates some variable of S with a variable of F. This implies that there can be an interaction involving two system S and F relative to a system W *only if there is a quantum state* $|\psi\rangle^{(W)}_{S\cup F}$.

As noted in Chapter 2, the basic structure of RQM implies that there can be no quantum state of a system relative to itself. Therefore, there can't be a quantum state of a system relative to one of its subsystems.[2] In other words, for any two systems S and F neither $|\psi\rangle^{(S)}_{S\cup F}$ (and $\rho^{(S)}_{S\cup F}$) nor $|\psi\rangle^{(F)}_{S\cup F}$ (and $\rho^{(F)}_{S\cup F}$) are defined. The conjunction of this fact and Interactions as Relative Correlations straightforwardly implies that for any two systems S and F, it would never be the case that an interaction between S and F occurs relative to either S or F. In other words, for any two systems S and F, events of the form $[e^{(F)}_S(\mathcal{V})]^S$, $[e^{(S)}_F(\mathcal{V}')]^S$, $[e^{(F)}_S(\mathcal{V})]^F$ or $[e^{(S)}_F(\mathcal{V}')]^F$ never occur. This would clearly be catastrophic for the prospects solving RQM's measurement problem, i.e. for the prospects of meeting the requirements that I set out in Chapter 3.[3]

In Chapter 3 I explained that RQM is required to explain the predictions of quantum mechanics in all of its successful applications. I argued that, for instance, in any experimental application of quantum theory, RQM needs to predict that an interaction between the scientist and the experimental apparatus *occurs relative to the scientist* such that, *relative to the scientist*, a pointer variable of the apparatus takes a value relative to the scientist. But I have just argued that Interactions as Relative Correlations has the

[2]Assume there is a quantum state $|\psi\rangle^{(F)}_{S\cup F}$ or $\rho^{(F)}_{S\cup F}$ of $S\cup F$ relative to one its subsystems, namely F. From this quantum state one may derive a (possibly impure) quantum state of F relative to F. That is not allowed by RQM, thus there cannot be a quantum state of a system relative to one its subsystems.

[3]Evidently, this problem also affects the probabilistic variant of this proposal, sketched in footnote 1 above.

implication that for any system two systems S and F, no interaction of the type $[e_S^{(F)}(\mathcal{V})]^F$ can occur. Hence Interaction as Relative Correlations is inadequate to meet the requirements set out in Chapter 3.

To resolve this issue, one might want to reduce the scope of Interactions as Relative Correlations, in the following way:

Weak Interactions as Relative Correlations: *For any two distinct systems F, S, a pair of events $e_S^{(F)}(\mathcal{V})$ and $e_F^{(S)}(\mathcal{V}')$ occur relative to any third system W **(distinct from** F or S) at a time t if and only if there is a quantum state $|\psi(t)\rangle_{S\cup F}^{(W)}$ or $\rho(t)_{S\cup F}^{(W)}$ of the two systems relative to W and such a quantum state predicts a perfect correlation between $\mathcal{V}$ and $\mathcal{V}'$.*

Weak Interactions as Relative Correlations does not state that events of the type $e_S^{(F)}(\mathcal{V})$ or $e_F^{(S)}(\mathcal{V}')$ never occur relative to either S or F. Instead it leaves open the possibility for their occurrence relative to S or F. However, it does not specify the circumstances in which such events do occur relative to S or F, because it only specifies the occurrence of events relative to *third* systems. Therefore, on its own, it is insufficient to meet the requirements set out in Chapter 3. More importantly, there is no clear way of extending the principle to cover the circumstances for the occurrence of events of the type $[e_S^{(F)}(\mathcal{V})]^F$ or $[e_F^{(S)}(\mathcal{V}')]^F$.

One might hope that an appeal to Internal Consistency might save the day. Unfortunately, exactly because of the problem under consideration, Internal Consistency can never be applied. Recall that according to Internal consistency *if* events $[e_S^{(F)}(\mathcal{V})]^F$ and $[e_F^{(S)}(\mathcal{V}')]^F$ occur, then all of the quantum states $|\psi\rangle_{S\cup F}^{(W)}$ or $\rho_{S\cup F}^{(W)}$ of $S \cup F$ relative to third systems (W) must predict a perfect correlation between the appropriate values of $\mathcal{V}$ and $\mathcal{V}'$. However, exactly because of the problem I have outlined, the antecedent in the statement of Internal Consistency is never satisfied, as events such as $[e_S^{(F)}(\mathcal{V})]^F$ and $[e_F^{(S)}(\mathcal{V}')]^F$ never occur. Thus, Internal Consistency can never be applied and it does nothing to relieve the problem under consideration.

In sum, Interactions as Relative Correlations and its Weak version are not adequate to satisfy the requirements set out in Chapter 3. At least prima facie, the natural resolution of this puzzle is positing that interactions are *absolute*. This proposal will be the focus of the next section.

4.3 Absolute Interactions as Correlations

One may resolve the problem above while holding onto a principle similar to Interactions as Relative Correlations by postulating that interactions are not relative, but rather absolute. The resulting principle for a specification of interactions is the following:

Absolute Interactions as Correlations: *A pair of events* $e_S^{(F)}(\mathcal{V})$ *and* $e_F^{(S)}(\mathcal{V}')$ *occur (absolutely) at a time* t *if and only if there is a quantum state* $|\psi(t)\rangle_{S\cup F}^{(W)}$ *or* $\rho(t)_{S\cup F}^{(W)}$ *of the two systems relative to a third system* W *and such a quantum state predicts a perfect correlation between* $\mathcal{V}$ *and* $\mathcal{V}'$*.*

The principle may be expressed in mathematical terms similarly to above.

Absolute Interactions as Correlations claims that correlations in *one* relative quantum state are enough for the absolute occurrence of an event. Given that, in general, relative quantum states differ, one might be worried that the resulting pattern of absolute events will be an incoherent mess, with wildly different interactions occurring at the same time for one system. One might think that it would be best to require the quantum states relative to *all* third systems to predict a perfect correlation, to avoid such a scenario. Interestingly this is unnecessary, as this problem is taken care of by Internal Consistency.

Suppose that a quantum state $|\psi\rangle_{S\cup F}^{(W)}$ or $\rho_{S\cup F}^{(W)}$ predicts a perfect correlations between the variables $\mathcal{V}$ and $\mathcal{V}'$ of, respectively, S and F. Then Absolute Interaction as Correlations implies that events $e_S^{(F)}(\mathcal{V})$ and $e_F^{(S)}(\mathcal{V}')$ occur, absolutely. Given that such events occur absolutely, Internal Consistency implies that *all* quantum states of $S \cup F$ relative to *all* third systems will predict the same correlations in the variables $\mathcal{V}$ and $\mathcal{V}'$, just like the quantum state $|\psi\rangle_{S\cup F}^{(W)}$ (or $\rho_{S\cup F}^{(W)}$) relative to W . In other words, the combination of Internal Consistency and Absolute Interactions as Correlations implies a great coordination among relative quantum states: if one quantum state $|\psi\rangle_{S\cup F}^{(W)}$ (or $\rho_{S\cup F}^{(W)}$) predicts perfect correlations in a given basis, then all quantum states of $S \cup F$ relative to all third systems must predict the same perfect correlations. Therefore, for any two systems S and F, the quantum states relative to all third systems W predict the same interactions, thus avoiding the risk of wildly different interactions at the same time for one and the same system. Note that this does not ensure that the interactions derived from Absolute Interactions as Correlations satisfy the requirements set out in Chapter 3. That still needs to be proven.

Just like Interactions as Relative Correlations, Absolute Interactions determines both an *exact* time at which interactions occur as well as *what* *variable* takes a value in each interaction, with the caveat that such variables which become determined might not be unique. Once again I will set aside this problem for section 4.4.

Given the assumption that the occurrence of interactions is absolute, Absolute Interactions as Correlations does not suffer from the problem described above. If there is a quantum state $|\psi\rangle^{(W)}_{S\cup F}$ (or $\rho^{(W)}_{S\cup F}$) with the right correlations, events of the kind $e^{(F)}_{S}(\mathcal{V})$ happen *absolutely* (i.e. not relatively), hence they will happen also for the systems F and S. As noted above, this is necessary for meeting the requirements set out in Chapter 3.

Unfortunately, Absolute Interactions as Correlations suffers from a fatal problem, which also highlights one way in which both Interactions as Relative Correlations and Absolute Interactions as Correlations are misguided attempts at cashing out the intuition of "interactions as correlations". The problem spawns from the Schmidt decomposition theorem (Peres, 1993) : for any pure quantum state $|\psi\rangle$ on a Hilbert space $\mathcal{H}_{\mathcal{S}\cup\mathcal{F}} = \mathcal{H}_{\mathcal{F}} \otimes \mathcal{H}_{\mathcal{S}}$, it is always possible to find orthonormal bases $\{|A_i\rangle\}$ and $\{|B_i\rangle\}$ of $\mathcal{H}_{\mathcal{F}}$ and $\mathcal{H}_{\mathcal{S}}$ such that:

$$|\psi\rangle = \sum_i \alpha_i |A_i\rangle |B_i\rangle$$

In other words, for any pure quantum state of any bipartite system, there always are perfectly correlated sets of variables of each system. The Schmidt decomposition theorem paired with Absolute Interactions as Correlations implies that any two systems S and F which have a pure quantum state relative to a third system at a time t are interacting at that time t. This is clearly unacceptable, for several reasons.

Firstly, the primary literature describes the ontology of RQM as a 'sparse flash ontology [... of] point-like quantum events or "flashes"' (Adlam and Rovelli, 2023, p.11). For instance, Laudisa and Rovelli (2019) claim that according to RQM 'the history of a quantum particle [...] with respect to any other system, it is a discrete set of interactions, each localized in spacetime.' (Laudisa and Rovelli, 2021, Section 2.2). Instead, because of the Schmidt decomposition theorem, Absolute Interactions as Correlations leads to somewhat *continuous* interactions. Inevitably, there will be many bipartite systems $S \cup F$ that have a pure quantum state relative to some other system for finite intervals I of time. Then, Absolute Interactions as Correlations implies that at all times $t \in I$ in such intervals F and S are interacting, in a somewhat *continuous* interaction where different variables take a value depending on which variables are perfectly correlated at any one time. Clearly, this is incompatible with RQM's supposed ontology.

More importantly, the dynamics of RQM simply breaks down in the case of continuous interactions. Recall that at each (absolute) event $e_S^{(F)}(\mathcal{V})$ the quantum state of S relative to F collapses to the relevant eigenstate. If systems have continuous interactions with one another, it is not clear how this dynamics may be applied.

The Schmidt decomposition theorem highlights one way in which both Interactions as Relative Correlations as well as Absolute Interactions as Correlations may not be capturing the essence of the "interactions as correlations" intuition. Both principles claim that a correlation in the quantum state relative to a third system indicates an interaction occurring *at that specific time.* However, it might be more appropriate that correlations relative to a third system only indicate that an interaction *has happened at some point in time before* and, instead, the occurrence of an interaction manifests through the *establishment* of correlations. In the next section I will explore such an avenue.

4.4 Interactions as the establishment of entanglement

I noted above that the intuition of "interactions as correlations" might be best characterised as the intuition that the *establishment* of correlations indicates the occurrence of an interaction. Quantum theory comes with a natural structure to characterise such an intuition: entanglement. Hence, in this section I will consider the principle according to which the establishment of entanglement between two systems indicates that an interaction has occurred.

For simplicity, I will only consider pure quantum states in this section.[4] Moreover, I will start by assuming a step-wise dynamics of the quantum state, namely, I will assume the quantum state is defined at discrete times $\{t_0, t_1, t_2 ...\}$ and it evolves in between these times. This approximation will be helpful to develop the intuition, but ultimately it ought to be relaxed.

Given the step-wise dynamics, the principle may be defined as follows:

Interactions as the Establishment of Entanglement: *An (absolute) interaction between two systems S and F occurs at a time t_n if an only if*

[4]The complexities added by impure quantum states are unnecessary to consider, given that ultimately this approach is not adequate anyway.

there is a quantum state $|\psi\rangle^{(W)}_{S\cup F}$ relative to a third system W such that

$$|\psi(t_{n-1})\rangle^{(W)}_{S\cup F} = |\psi\rangle^{(W)}_{S} \otimes |\psi\rangle^{(W)}_{F}$$

namely the quantum state of $S \cup F$ relative to W is separable at t_{n-1}, and the quantum state of $S \cup F$ relative to W is not a separable state at t_n, i.e. it is an entangled state. At such interaction, events $e^{(F)}_{S}(\mathcal{V})$ and $e^{(S)}_{F}(\mathcal{V}')$ occur if and only if the $|\psi(t_n)\rangle^{(W)}_{S\cup F}$ predicts a perfect correlation between $\mathcal{V}$ and $\mathcal{V}'$.

In other words, when a relative quantum state of $S \cup F$ turns from unentangled to entangled relative to any one third system, an interaction occurs.

Before criticising this principle, I note two features of it. First, in order to avoid the problems that Interactions as Relative Correlations faces, Interactions as the Establishment of Entanglement assumes absolute interactions. Secondly, the Schmidt decomposition theorem poses no threat to this principle, since it is only when entanglement is *established* that an interaction occurs.

Unfortunately, Interactions as the Establishment of Entanglement faces a number of fatal problems. First, as pointed out by Pienaar (2021) and Brukner (2021),[5] it faces the preferred basis problem. They note the familiar fact that certain quantum states of bipartite systems admit more than one Schmidt decomposition. In particular, if some of the Schmidt coefficients are equal, then the decomposition is not unique. I will borrow an example from Brukner (2021). Consider two spin-$\frac{1}{2}$ systems F and S such that their

[5] Although Pienaar's (2021) and Brukner's (2021) objection applies, it's worth noting that they might not have in mind exactly the notion of interaction that I am attempting to construct here.

quantum state relative to W evolves from an unentangled state at t_{n-1} to the following entangled state at t_n:

$$|\psi(t_n)\rangle^{(W)}_{S\cup F} = \frac{1}{\sqrt{2}}(|\uparrow\rangle_F |\uparrow\rangle_S + |\downarrow\rangle_F |\downarrow\rangle_S)$$

This quantum state predicts a perfect correlations between spin-z states. Hence, according Interactions as the Establishment of Entanglement there is an interaction between F and S at time t_n resulting in events $e^{(F)}_S(spin \quad z)$ and $e^{(S)}_F(spin \quad z)$. However, consider re-writing the quantum state in the spin-x basis:

$$|\psi(t_n)\rangle^{(W)}_{S\cup F} = \frac{1}{\sqrt{2}}(|{+x}\rangle_F |{+x}\rangle_S + |{-x}\rangle_F |{-x}\rangle_S)$$

The basis change may be easily checked given $|\uparrow\rangle = \frac{1}{\sqrt{2}}(|{+x}\rangle + |{-x}\rangle)$ and $|\downarrow\rangle = \frac{1}{\sqrt{2}}(|{+x}\rangle - |{-x}\rangle)$. This form of the quantum state makes manifest that $|\psi\rangle^{(W)}_{S\cup F}$ also predicts perfect correlations between spin-x states. Therefore, according to Absolute Interactions as Correlations there also is an interaction resulting in events $e^{(F)}_S(spin \quad x)$ and $e^{(S)}_F(spin \quad x)$. This result is puzzling, and requires making sense of a system having a determined value for both spin-z and spin-x.

There might be no conceptual problem with two distinct variables taking a value at once.[6] However, if the mathematical apparatus of quantum theory

[6] A proposal by Adlam and Rovelli (2023) to embrace multiple variables taking a value at an event is considered in Chapter 6. Moreover, note an interesting connection with the famous EPR argument (Einstein et al., 1935), where it was argued that both momentum and position ought to be determinate, if quantum theory was to respect some locality and completeness constraints.

is to be kept unmodified (as per aim (3) of RQM, see Section 2.1), there is a technical problem in the case of incompatible variables. Recall that, according to RQM, at any interaction resulting in an event $e_S^{(F)}(\mathcal{V} = v)$, the relative quantum state collapses to the relevant eigenstate $|\psi\rangle_S^{(F)} \to \frac{\Pi_v|\psi\rangle_S^{(F)}}{|\Pi_v|\psi\rangle_S^{(F)}|}$, where Π_v is the projector associated with the value v of the quantity $\mathcal{V}$. Suppose that two variables $\mathcal{V}$ and $\mathcal{V}'$ take values v and v' at an interaction. If these two variables correspond to compatible observables, no problem arises: the quantum state simply collapses into a simultaneous eigenstate of both variables. Or, more precisely, $|\psi\rangle_S^{(F)} \to \frac{\Pi_v\Pi_{v'}|\psi\rangle_S^{(F)}}{|\Pi_v\Pi_{v'}|\psi\rangle_S^{(F)}|} = \frac{\Pi_{v'}\Pi_v|\psi\rangle_S^{(F)}}{|\Pi_{v'}\Pi_v|\psi\rangle_S^{(F)}|}$. However, if the two variables are incompatible, just like in the case of spin-x and spin-z, there is no shared eigenbasis, and thus it remains undefined whether the quantum state $|\psi\rangle_S^{(F)}$ ought to collapse onto an eigenstate of spin-z or an eigenstate of spin-x. In precise mathematical terms, if $\mathcal{V}$ and $\mathcal{V}'$ are incompatible variables, then $\Pi_v\Pi_{v'}\,|\psi\rangle_S^{(F)} \neq \Pi_{v'}\Pi_v\,|\psi\rangle_S^{(F)}$, thus it is not defined which one of the two states is the final collapsed state.

However, the problem of the preferred basis is not limited to cases of quantum states with multiple Schmidt decompositions. If the approximation of a step-wise evolution of the quantum state is lifted, one notes that the entanglement of the quantum state of $S \cup F$ relative to W is a continuous process occurring over a certain period of time. In most realistic interactions, the process will not have a exact beginning or end. Then the entanglement correlations between the systems will continuously change during the time in which the entanglement process occurs. Without further information, there is no clear rule to determine exactly which of the different variables that are perfectly correlated at different times of the evolution are the ones which become determinate.

In response to Pienaar's and Brukner's objections, Di Biagio and Rovelli (2022) deny the necessary and sufficient link between interactions and correlations in quantum states relative to third systems. As I note below, they argue that the dynamics plays instead a crucial role. I agree that looking into the Hamiltonian offers better chances of defining the circumstances in which interactions occur. However, I am not motivated by the preferred basis problem – as I will show below, it is not clear that an appeal to the structure provided by the Hamiltonian offers much of a solution to the preferred basis problem in RQM. Instead, there are other problems in Interactions as Entanglement Correlations which motivate an exploration of the structure of the Hamiltonian in order to define interactions. I will present such problems in the rest of this section, and I will postpone a full discussion of the preferred basis problem to Chapter 6.

Fundamentally the problem is that there are strong indications that Interactions as the Establishment of Entanglement does not select the right kinds of interactions. First, it may face difficulties in predicting multiple interactions between the same two systems. Suppose the quantum state of a bipartite systems $S \cup F$ relative to W becomes entangled at a time t_n. Then, an absolute interaction between S and F occurs resulting in (absolute) events $e_S^{(F)}(\mathcal{V})$ and $e_F^{(S)}(\mathcal{V}')$. Can RQM predict that another interaction occurs between S and F, soon after t_n, for instance, at t_{n+1}? For RQM to predict so, there needs to be *a* quantum state relative to *a* system which is unentangled at t_n and entangled at t_{n+1}. The quantum state $|\psi\rangle_{S\cup F}^{(W)}$ cannot be of any help, since it is already entangled at t_n. Moreover due to Internal

Consistency, all quantum states of $S \cup F$ at t_n relative to any third system are going to be such that they predict perfect correlations between the variables that have taken a value at the original interaction. For simplicity, let me limit myself to the case of pure quantum states. All pure quantum states of $S \cup F$ relative to a third system will be of the form $\sum_i \alpha_i |v_i\rangle \otimes |v'_i\rangle$. Therefore there can be an interaction between systems S and F at a time t_{n+1} *only if* at least relative to one third system W' the quantum state of $S \cup F$ is of the form $|v_l\rangle \otimes |v'_l\rangle$ and becomes entangled at t_{n+1}. Although by no means this is a knockdown objection, it does not seem appropriate for the occurrence of multiple (absolute) interactions between two systems to depend on whether there is *a* quantum state of *a* third system which is exactly a product state.

Secondly, there are many cases in which entanglement between two systems may arise without what ought to be called an interaction. For instance, consider two particles A and B in a singlet state relative to a system W which are far apart from each other. Suppose that particle A is in the vicinity of a scientist named Alice.[7] A local unitary operation which entangles Alice and A will also entangle Alice and B. Therefore, an interaction between Alice and B occurs, even though Alice and B are far away from each other and, at least intuitively, seem not to have interacted. Another similar, but possibly more extreme example is the vaccuum state of spacelike separated regions of spacetime in quantum field theory on Minkowski spacetime: it does not seem appropriate to claim that there have been interactions between such spacelike separated regions of space, but their quantum states are entangled.

[7] Whatever the ontology of RQM, it needs to be able to recover the arising of this situation relative to an observer, at least apparently.

Both of these examples imply clashes with the intended picture of the ontology of RQM as a 'sparse flash ontology [... of] pointlike quantum events or "flashes"' (Adlam and Rovelli, 2022).

Ultimately, these two latter issues strongly indicate that the structure of entanglement is not enough to specify appropriate circumstances for the occurrence of interactions in RQM, at least on its own. Instead, it seems more appropriate to include considerations of the *dynamics* which governs the quantum states themselves. The fact that we talk of a local unitary entangling Alice and A should give some indication that an interaction occurs between Alice and A only. More recent writings in the primary literature also seem to share this conviction:

> Pienaar and Brukner take the state as primitive and assume that out of the state one can deduce which events happen in a composite system. This is not RQM. In RQM, it is the other way around. Events are primitive. Their happening is partially reflected in the state of the composite system relative to a third system. But only partially. Events cannot be read out of the state. The existence of a correlation between two variables gives indications about events, but in general it is not sufficient to tell which event was or was not realised. To know what event lead to the creation of a correlation, one needs to know more, for example the dynamics that coupled the two systems and, in particular, what variables are involved in the interaction. (Di Biagio and Rovelli, 2022, p.5)

Thus, in the next chapter, I will explore how can one use the dynamics to define the circumstances in which interactions occur.

Chapter 5

Interactions via the dynamics

As noted in the previous chapter, Di Biagio and Rovelli (2022) assert that one may not derive the occurrence of events only by looking into correlations in the quantum state:

> (i) a variable of S has a value with respect to F, and (ii) with respect to W, there is a correlation to be expected between a variable of S and a pointer variable of F. The first implies the second, but the second does not imply the first. (Di Biagio and Rovelli, 2022, p.8)

Instead, they maintain that the key lies in the dynamics:

> To know what event led to the creation of a correlation, one needs to know more, for example the dynamics that coupled the two systems and, in particular, what variables are involved in the interaction. (Di Biagio and Rovelli, 2022, p.5)

Thus, Di Biagio and Rovelli claim that one needs to look into 'the dynamics that coupled the two systems' (*ibid*) in order to understand what event occurred. A passage in Rovelli's (2021) reply to Muciño et al. (2022) might offer more information of what exactly that involves:

> 'Which variable takes a value in the interaction is dictated by the physics: in the classical theory, we can describe the interaction between the two systems, say, in terms of an interaction term in the Hamiltonian that depends, in particular, say, on a variable A of the system S: then A is the value that takes value. The reason is that the interaction Hamiltonian depends on the property of S responsible in determining the effect of S on O. And this is precisely how quantum theory describes the world (in RQM): the way systems affects one another.' (Rovelli, 2021, p.3)

In this passage, Rovelli appeals to interaction terms in the Hamiltonian as a description of the dynamics which determines the interaction between two systems, as it is standard in the practice of physics. One gets the impression that questions concerning which systems interact, and in what way, ought to be answered by appealing to the form of the Hamiltonian, in particular, by looking at which interaction terms are present in the Hamiltonian of the systems. More generally, from the absence of a definition of the notion of interaction in the writings of Rovelli and his collaborators, one gets the impression that they are appealing to a "standard" notion of interaction, as used in the practice of physics. In the present chapter, I will explore the possibility of appealing to the standard notion of interactions to capture the occurrence of RQM's interactions.

First, I will explore how one could go about this task in a simpler setting, where variables and states are absolute. There are some difficulties in that setting, but there are also good prospects of fixing them. Once this standard picture has been laid out, I will attempt to extend the approach to RQM's ontology and basic framework. In this latter context I will encounter severe difficulties.

In order to extend the approach to the context of RQM, I will need first to explore and define precisely the status of the Hamiltonian in RQM, a topic which was set aside in Chapter 2. I will find out that the Hamiltonian in RQM ought to be conceptualised as a relative entity. I will show that the relativity of the Hamiltonian and the relativity of quantum states suggests that, if interactions are to be defined from the dynamics, the occurrence of interactions is relative, not absolute. However, given the relativity of the occurrence of the interactions, the same problem affecting Interactions as Relative Correlations will be encountered (see section 4.2).

In order to address the problem, I will attempt to implement a similar mechanism to define interactions under the assumption that the occurrence of interactions is absolute. Unfortunately, the most plausible ways to specify the occurrence of absolute interactions will fail to offer a picture compatible with the basic framwork of RQM, or at least an empirically adequate picture. Interestingly, some of the arguments I offer suggest that, in order to obtain absolute interactions, one must posit absolute outcomes, in some sense. However, no satisfactory way to do so within the framework of RQM is found, rather it appears that a global collapse of the wavefunction or the introduction of many-worlds may be necessary.

5.1 Dynamics and interactions in the context of absolute states and absolute dynamics

5.1.1 Dynamics and sequences of interactions:

Before tackling the challenge of defining interactions within the ontology of RQM, it is convenient to attempt the task in the simpler setting of absolute variables and absolute states.

In quantum theory, two systems S and F with a Hilbert space $\mathcal{H} = \mathcal{H}_S \otimes \mathcal{H}_F$ are said to be interacting *only if* the Hamiltonian governing the evolution of their quantum state contains an interaction term $H_{S\cup F}$, namely a term which cannot be decomposed in terms acting only on the subspaces $\mathcal{H}_S$ and $\mathcal{H}_F$:

$$H_{S\cup F} \neq H_S \otimes \mathbb{1}_2 + \mathbb{1}_1 \otimes H_F$$

I will call operators which cannot be so decomposed *non-separable over the Hilbert space* $\mathcal{H}_S \otimes \mathcal{H}_F$.[1]

The presence of a non-separable interaction term is naturally taken as a necessary condition for interaction for the following reason. If the Hamiltonian of S and F were separable, the evolution of the quantum state of one system would be independent of the quantum state of the other. Consequently the probabilities of values for quantities of one system would evolve independently from the probabilities of values for quantities of the other system. Thus, there may be a dependency between the quantum states of the

[1] Note this notion of non-separability is different from the notion of non-separability as applied to quantum states.

two systems *only if* the Hamiltonian is non-separable.

As I argue in more detail below, the Hamiltonian being non-separable should be taken as a necessary but insufficient condition for the occurrence of an interaction. However, one might still attempt to use this formalism alone to define the circumstances for the occurrence of interactions within the quantum formalism: roughly, an interaction between two systems occurs if and only if the Hamiltonian of the systems involves an interaction term non-separable over the Hilbert spaces of the two systems. In RQM a system will undergo many interactions and, in Section 3.4, I have argued that RQM is required to offer a specification which indicates the occurrence of events and which, at least in some cases, must also determine an order between certain events.[2] To meet such a requirement, this approach seems to require a principled way to derive a sequence of sets of interaction terms $\Gamma_S = \langle ...\{H_{S\cup S_i}, H_{S\cup S_{i+1}}, ...\}, \{H_{S\cup S_j}, H_{S\cup S_{j+1}}, ...\}...\rangle$ for each system S, where each interaction term $H_{S\cup S_i}$ is non-separable over Hilbert space $\mathcal{H}_{\mathcal{S}} \otimes \mathcal{H}_{S_i}$ and thus associated with an interaction between S and S_i. Γ_S provides a natural way to define a list of interactions and a weak order among them. A sequence Γ_S naturally settles which systems S interacts with and the order of such interactions, but it does not settle what variables become determined at such interactions. I will set that problem aside for now.

This proposal leads to an immediate question: how is one supposed to derive a sequence Γ_S of sets of interaction terms? In the practice of physics, a quantum model of certain systems is specified via three elements. A Hilbert

[2]Recall that, although one might give into Adlam and Rovelli's claim that events to not have *precisely* defined times, in order to correctly explain experimental predictions, RQM must predict the order among certain kinds of events.

space $\mathcal{H}$ with a specific decomposition into the individual systems' Hilbert spaces $\mathcal{H} = \mathcal{H}_1 \otimes \mathcal{H}_2$.... An algebra of self-adjoint operators on $\mathcal{H}$, which are usually called "observables". Finally, an (often time-independent) preferred operator: the Hamiltonian H. Given a certain collection of systems in a certain physical situation, there are some rules regarding what quantum model should be used to model them. However, each quantum model is assigned a single Hamiltonian, and a single set of interaction terms, rather than a sequence of Hamiltonians. Thus, one cannot straightforwardly appeal to the rules for defining quantum models in the practice of physics in order to define a sequence of sets of interaction terms for each system.

5.1.2 Defining Γ_S in the context of absolute values and absolute quantum states

In what follows, I will explore a natural proposal for deriving such a sequence, namely deriving it from a universal Hamiltonian. I will show that such a proposal is promising, but that more work is needed to show that it satisfactorily meets the requirements set in Chapter 3. More generally, I intend to show two things. Firstly, that one may not take for granted that it is possible to define a principled method to derive such a sequence Γ_S such that it appropriately answers the concerns set out in Chapter 3. Secondly, that the choice of a series Γ_S is necessarily correlated with the quantum state of S (and possibly other systems).

A natural, principled way of assigning a series of Hamiltonians to a system might proceed along the following lines. *Really*, the quantum states of systems are governed by a global, time-independent Hamiltonian of the whole universe and the justification for assigning a certain Hamiltonian to a given quantum model is that, for the relevant collection of systems, it approximates well the universal Hamiltonian. Such a universal Hamiltonian will involve an extremely large amount of free and interaction terms and, for a given interval of time, many of those will have a negligible or null effect on the relevant collection of systems. What is left over after ignoring such terms is the Hamiltonian for the quantum model of the given collection of systems in the given interval of time.

This reasoning seems to afford a method to derive a sequence of interaction terms for a single system over time, at least in principle. The interaction terms which have not been deemed to have a negligible or null effect on a system in a given interval of time denote the interactions that occur in such interval of time. Which terms have a null or negligible effect on a system changes over time, and thus one might derive a sequence of sets of interaction terms for a system for each given interval of time.

This approach of neglecting certain terms in the universal Hamiltonian goes hand-in-hand with my claim that the presence of a non-separable interaction term in the Hamiltonian is insufficient to denote an interaction. This consideration is obviously necessary if one believes that the *true* Hamiltonian of the system is the universal Hamiltonian, which does not change with time and involves an extremely large number of interaction terms for each system. Indeed, I claim that interaction terms ought not to be considered as denoting an interaction if they have a null effect on the relevant pair of systems. Crucially, the only way to evaluate how a term of the Hamiltonian affects a system is by looking into the effects of that term on the quantum state of the system. It is instructive to consider a simple 2-systems case.

Consider two systems S and F with a Hilbert space $\mathcal{H} = \mathcal{H}_S \otimes \mathcal{H}_F$ and a Hamiltonian $H = H_0 + H_{S\cup F}$, where H_0 is the free (separable) term in the Hamiltonian and $H_{S\cup F}$ is the interaction (non-separable) term. If $H_{S\cup F}$ is to denote an interaction between S and F, it must somehow influence the evolution of the two systems. A natural formalisation of such a condition is the following:

Non-Interaction (2 systems case): *Two systems S and F have not interacted in the interval of time $[t, t + \Delta t]$ if and only if for all $\delta t \leq \Delta t$:*

$$|\psi(t+\delta t)\rangle_{S\cup F} = e^{-\frac{i}{\hbar}(H_0+H_{S\cup F})\delta t}\,|\psi(t)\rangle_{S\cup F} = e^{-\frac{i}{\hbar}(H_0+\alpha)\delta t}\,|\psi(t)\rangle_{S\cup F}$$

where $\alpha \in \mathbb{R}$.[3]

Interestingly, this condition is equivalent to the quantum state $|\psi\rangle_{S\cup F}$ being an eigenstate of $H_{S\cup F}$. Non-Interaction (2 systems case) is a natural condition for non-interaction, because it is equivalent to the following: the interaction potential $H_{S\cup F}$ does not denote the occurrence of an interaction in the time interval $[t, t + \Delta t]$ if and only if the probabilities associated with the values of all observables of the system $S \cup F$ are left unchanged by the potential $H_{S\cup F}$.[4]

[3]Note: the first equality is just explanatory, the second is the only substantive constraint.

[4]Another plausible condition may be considered: two systems S and F have not interacted in the interval of time $[t, t + \Delta t]$ if and only if for all $\delta t \leq \Delta t$ the density operator ρ_S and ρ_F of each individual system is unchanged by $H_{S\cup F}$. However there are potentials which change the probabilities of global observables of $S \cup F$ without changing the proba-

The condition may be easily generalised to the realistic case of more than two systems. Consider a collection of systems $\{S_i\}$ with a Hilbert space $\mathcal{H} = \otimes_i \mathcal{H}_{S_i}$. One may express a Hamiltonian defined over such a space as a sum of free and non-separable terms:

$$H = H_0 + H_{S_1 \cup S_2} + H_{S_1 \cup S_3} + ... + H_{S_2 \cup S_3} + H_{S_2 \cup S_4} + ... + H_{S_1 \cup S_2 \cup S_3} + H_{S_1 \cup S_3 \cup S_4} + ...$$

where H_0 is the sum of the free Hamiltonians for each system and $H_{S_i \cup S_j \cup S_k \cup ...}$ is the interaction Hamiltonian non-separable over $\mathcal{H}_{S_i} \otimes \mathcal{H}_{S_j} \otimes \mathcal{H}_{S_k} \otimes ...$. Then:

Non-Interaction Condition: *Consider a Hilbert space $\mathcal{H} = \mathcal{H}_s \otimes \mathcal{H}_{S_i} \otimes \mathcal{H}_{S_2} \otimes ... \otimes \mathcal{H}_{S_N}$. Two systems S and F have not (directly) interacted in the interval of time $[t, t + \Delta t]$ if and only if for all $\delta t \leq \Delta t$:*

$$\rho_{S \cup F}(t + \Delta t) = Tr_{\mathcal{H} \backslash \mathcal{H}_S \otimes \mathcal{H}_F}(e^{-\frac{i}{\hbar} H \delta t} \rho(t) e^{\frac{i}{\hbar} H \delta t}) = Tr_{\mathcal{H} \backslash \mathcal{H}_S \otimes \mathcal{H}_F}(e^{-\frac{i}{\hbar}(H - H_{S \cup F})\delta t} \rho(t) e^{\frac{i}{\hbar}(H - H_{S \cup F})\delta t})$$

where $\alpha \in \mathbb{R}$ and $F \in \{S_1, S_2, ..., S_1 \cup S_2, S_1 \cup S_3, ..., S_1 \cup S_2 \cup S_3, ...\}$.[5]

As above, this condition rules that an interaction potential $H_{S \cup F}$ does not indicate the occurrence of a (direct) interaction during the time interval $[t, t + \Delta t]$ if and only if the probabilities associated with observables of the system $S \cup F$ are unchanged by $H_{S \cup F}$ in the interval of time. I will call interaction terms which do not satisfy the equality in the Non-Interaction Condition *active* terms. These are the terms which indicate the occurrence of interactions.

bilities of observables of S or F. This latter revised rule would rule those as not denoting an interaction. That seems wrong. Hence Non-Interaction (2 systems case) is preferrable.

[5] As above, the first equality is only explanatory, the second is the only substantive constraint.

The attentive reader will have noted that in the present discussion I consider *direct* interactions, rather than interactions simpliciter. The reason is the following. According to the above definition, even if there is no direct interaction between systems S and F, there might be a direct interactions between S and one of the subsystems of F or S and a system that F is a subsystem of. One might be tempted to claim that such direct interactions induce *indirect* interactions between S and F. In what follows I will mostly set aside the questions around such indirect interactions, as we will have more pressing problems to solve and, unless stated otherwise, the term 'interaction' will only refer to direct interactions.

If one partitions time into a sequence of intervals, the Non-Interaction Condition naturally defines a sequence of sets of interaction terms, corresponding to the terms which are are active in each of the intervals of time. Is such a sequence an acceptable answer to the requirements set out in Chapter 3? It is not clear. There are serious problems with the sequences that the Non-Interaction Condition leads to. Some might be easily fixed, some might need some more technical work. For example, consider the following apparent problems.

First, the Non-Interaction Condition does not deliver a sequence of interaction terms. It delivers a sequence of *sets* of interaction terms. Thus it defines a non-strict order among interactions. However, it must be shown that, for all experimental applications of quantum theory, the sequence defines an appropriate order among the appropriate interactions, in order to correctly explain the predictions of quantum theory.

Secondly, it seems very unlikely that an *exact* condition like the Non-

Interaction Condition would rule out enough interaction terms to lead to an acceptable sequence of sets. Most likely each set would contain far too many interaction terms.[6] In order to resolve this issue, one might have to resort to an approximate condition, namely, one might need to claim that when the equation in the Non-Interaction Condition *approximately* holds, then the relevant interaction term is not active.

An appeal to an approximate condition might raise some worries, since whether an interaction occurs or not in the sense required for RQM cannot depend on a human decision of what level of approximation seems appropriate. However, such an approximate condition should not be taken to determine whether an interaction occurs or not, but rather it might be viewed as our imperfect attempt to individuate the interactions which occur. As long as it delivers clear answers which allow for correct predictions in the experimental cases and as long as it sufficiently indicates the existence of interactions also outside of experimental situations, the approximate condition meets the requirements set out in Chapter 3.

Thirdly, there are cases in which interactions collectively (approximately) screen each other, but individually they might not. Consider, for instance,, an electron in hydrogen atom, which is sitting sitting close to an (electrically neutral) large piece of matter. Call the electron in the Hydrogen atom S.

[6] It's easy to see once one considers that a great number of realistic interactions have an infinite range. Suppose S is an electron. Then, in principle, the total Hamiltonian will include a Coloumb interaction term with all other charged systems in the world. None of those terms are going to be inactive according to the Non-Interaction Condition, since their range is infinite. Thus, the Non-Interaction Condition implies that at any one interval of time an electron has interacted with all other electrons. Relativistic constraints might suggest that only the electrons in S's past light-cone matter. Even so, they would seem to be far too many.

Collectively, the Coloumb interactions between S and the electrons and protons in the large piece of matter may well approximately cancel each other out. Thus it may seem appropriate to claim that S is not interacting with all of the charged particles in the piece of matter, rather it might only be interacting with the proton in its own Hydrogen atom. But when considering an individual interaction term $H_{S \cup e}$ where e is an electron in the piece of matter, the Non-Interaction Condition might not hold. Once again an appeal to approximation might help.

Although these problems do not seem to show that the Non-Interaction Condition is doomed, they certainly show that the condition needs to be tweaked and most likely it will need to be turned into an approximate condition. However, as I explained above, my intention here is not to deliver an ultimate verdict on whether one may find such a principled way to define acceptable sequences of interaction terms. Instead, I aimed to prove, firstly, that it cannot be taken for granted that a *principled* method to derive a sequence of (sets of) interaction terms which satisfies the requirements set out in Chapter 3 may be found and, secondly, that what interaction terms end up in the sequence will *necessarily* be somewhat dependent or correlated with the quantum state of the relevant system.

It's worth remarking further on this second point. One might reject the Non-Interaction Condition and even reject *in toto* the idea that interaction terms for a system S should be derived from the universal Hamiltonian.[7] Even so, the sequence of interaction terms for a system S will depend or

[7] One may even doubt that talking about a universal Hamiltonian is sensible, or whether it is naïve, unhelpful fiction.

be correlated with the quantum state of the system S, due to the following fact. Any method for choosing interaction terms for a system must agree with the Hamiltonians used for tested and experimentally verified quantum models. Our practice of assigning Hamiltonians to quantum models takes into account the quantum state of the systems involved in the model (or at least, it accounts for information which is correlated with quantum states of the systems). For example, consider a proton and an electron. If their wavefunctions are sharply localised at opposite ends of the Earth, one would not model them with the Hydrogen Hamiltonian (in fact, one might not know how to model them at all), but if their wavefunctions show they are close enough (and far away enough from other particles) in the position representation, the hydrogen Hamiltonian may be appropriate. Thus, it is clear that, if the interaction terms included in the sequence are to match the tested and experimentally verified models of quantum mechanics, there is going to be some dependency between such a sequence of interaction terms and the quantum state of the relevant system.

Up to now, I have limited the discussion of how to derive a sequence of interaction terms Γ_S to the simpler scenario case in which values of variables and quantum states are absolute. I will now attempt to employ similar techniques to determine a sequence Γ_S in the context of relative values and relative quantum states.

5.2 Dynamics and interactions in the context of RQM

5.2.1 The Hamiltonian in RQM and the relativity of Γ_S:

In order to understand how to develop a sequence Γ_S of interaction terms for a system S in the context of RQM, one needs to get a grip on the status of the Hamiltonian in RQM. In Chapter 2, I set aside explorations of the status of the Hamiltonian in RQM, since, as we are about to find out, they do not have a straightforward answer. Nonetheless, the time has come to offer such answers. Once the status of the Hamiltonian is made clear, I will then proceed to consider the derivation of a sequence of sets of interaction terms Γ_S for a system S.

Here I will make three claims. First, the Hamiltonian in RQM should be understood as *relative*. Secondly, the sequences of interaction terms involving a system S will differ if computed relative to different systems. Thirdly, which interaction terms end up in a sequence $[\Gamma_S]^W$ for S relative to W will depend on the quantum state of S and other systems relative to W.

As above, in order to prove these claims, it is helpful to start under the assumption that one is looking for a universal Hamiltonian and then proceed to relax this assumption.

One might hope to be able to define a universal, absolute Hamiltonian.[8]

[8]One might wonder why not just having different and unrelated Hamiltonians relative to each system. That might turn out to be a coherent option, but one might not be able to fund any shadow of an objective/absolute element to our world within such a

In order to understand whether a universal, absolute Hamiltonian may be defined within the conceptual framework of RQM, one should first reflect on the kinds of considerations which are involved in the assignment of a universal Hamiltonian. The terms contained in a universal Hamiltonian would be determined by what features of the systems in the world posses. For example, if a system S has a certain mass m_S, then the universal Hamiltonian will contain the corresponding term. If it has an electric charge, the universal Hamiltonian will include the relevant electromagnetic interaction terms with all other charged systems. And so on. As noted by Healey (2022, p.5) and Dorato and Morganti (2022, p.2), the primary literature seems to stress the relativity only of the quantities which are associated with an observables (i.e. operators). Other quantities, such as the quantities used in determining the terms in a universal Hamiltonian (charge, mass, spin, ...) are not taken to be relative.[9] Thus, there is a sense in which one might speak of a universal, absolute Hamiltonian H_g on the Hilbert universal Hilbert space $\mathcal{H}_g$ for all systems. But a brief reflection on the role and use of the Hamiltonian within RQM shows that such universal H_g does not perform the roles that RQM needs it to.

In RQM, the Hamiltonian is the operator which determines the evolution of relative quantum states outside of interactions, during which the collapse postulate applies instead. As noted in Chapter 2, relative to a system F, not

description of unrelated relative states and unrelated relative Hamiltonians. Clearly an unappealing option, which would not do justice to RQM's core idea that 'In quantum mechanics different observers may give different accounts of the *same sequence of events*' (Rovelli, 1996, emphasis mine).

[9]These quantities would typically be state-dependent in relativistic quantum field theory, and thus relative within the conceptual scheme of RQM. This would seem to complicate things even further for RQM. Thus, I will focus on non-relativistic QM here.

all systems have a quantum state. For simplicity, I assumed that, relative to F, there is a quantum state of all systems different from F. However, the basic conceptual framework of RQM does not allow for self-ascription of a quantum state, thus no system has a quantum state relative to itself. For each system S_i one may define a Hilbert space $\mathcal{H}^{(S_i)}$ containing the Hilbert spaces of all systems apart from the Hilbert space of S_i itself. The universal Hamiltonian H_g mentioned above is instead on a Hilbert space $\mathcal{H}_g$ where the quantum states of *all* systems are defined. Therefore, $\mathcal{H}_g$ is necessarily different from each $\mathcal{H}^{(S_i)}$, and H_g cannot perform the roles that are required of it in RQM. Instead, in order to define the evolution of quantum states relative to each system S_i, one needs a Hamiltonian defined on the relative Hilbert space $\mathcal{H}^{(S_i)}$. This would result in many, relative Hamiltonians $H^{(S_i)}$, even if the $\mathcal{H}^{(S_i)}$ are all subspaces of $\mathcal{H}_g$.

Notwithstanding the different, relative Hilbert spaces $\mathcal{H}^{(S_i)}$, one might still hope to appeal to the universal, absolute Hamiltonian H_g to define the evolution of the relative quantum states. One might note that we often define the effects of a universal Hamiltonian on a smaller Hilbert spaces, via the operation of a partial trace. For instance, consider two systems S and F with a Hilbert space $\mathcal{H} = \mathcal{H}_S \otimes \mathcal{H}_F$ and Hamiltonian $H_{S \cup F}$ defined over it. Suppose the Hamiltonian $\mathcal{H} = \mathcal{H}_S \otimes \mathcal{H}_F$ generates a propagator $U_{S \cup F}(t)$. Then one may obtain the evolution of the density operator of one of the systems (say S) by tracing out the other Hilbert space:

$$\rho_S(t) = Tr_F(\rho_{S \cup F}(t)) = Tr_F(U_{S \cup F}(t)\rho_{S \cup F}(0)U^{\dagger}_{S \cup F}(t))$$

One might even use this to define a time evolution map $\mathcal{L}(t)$ for $\rho_S(t)$:

$$\mathcal{L}(t)\rho_S(0) \coloneqq Tr_F(U_{S\cup F}(t)\rho_{S\cup F}(0)U^\dagger_{S\cup F}(t))$$

One might hope to apply this in the context of RQM, in order to define maps $\mathcal{L}^{(S_i)}(t)$ from the universal Hamiltonian H_g which would define the evolution of relative quantum states in the relevant Hilbert space as follows. Define the collection of Hilbert spaces of the systems which have a quantum state relative to S_i as Ω_{S_i}. Then:

$$\mathcal{L}^{(S_i)}(t)\rho^{(S_i)}_{\Omega_{S_i}}(0) \coloneqq Tr_{universal\setminus\Omega_{S_i}}(U_{universal}(t)\rho^{(S_i)}_{universal}(0)U^\dagger_{universal}(t))$$

where $\rho^{(S_i)}_{\Omega_{S_i}}$ is the density operator of the collection of systems which have a quantum state relative to S_i, $Tr_{universal\setminus\Omega_{S_1}}$ is the partial trace over all Hilbert spaces apart from the ones belonging to the systems which have a quantum state relative to S_i, and $\rho^{(S_i)}_{universal}$ is the density operator of *every system in the universe* relative to S_i. Obviously, this proposal cannot work, simply because the problem itself is that $\rho^{(S_i)}_{universal}$ is undefined. Thus, in order to define the relative global Hamiltonians one needs to turn somewhere else.

One natural option is to construct the relative global Hamiltonians $H^{(S_i)}$ as if S_i itself were not to exist. In such a case, $H^{(S_i)}$ would contain all the terms in H_g which do not act on the subspace $\mathcal{H}^{(S_i)}$ associated with S_i, namely the terms that can be written as $O = \mathbb{1}_{S_i} \otimes O_{universe\setminus S_i}$. Another possible option is to posit an arbitrary, fixed of S_i relative to S_i, for mere computational purposes, such as the maximally mixed state. This would allow one to define $\rho^{(S_i)}_{universal}$ and compute a time evolution operator $\mathcal{L}^{S_i}(t)$ as detailed above. $\mathcal{L}^{S_i}(t)$ would be non-unitary in general, but might approximate unitarity in certain contexts. In either case, I have shown that any "global" Hamiltonian (or time evolution map) which is responsible for the evolution of the quantum states in RQM is a *relative* global Hamiltonian (or relative time evolution map). All that I say below is compatible with either option but, for ease, I will only mention relative global Hamiltonians.

From such relative global Hamiltonians $H^{(S_i)}$ one may attempt to define sequences of interaction terms. The fact that such sequences are derived from relative Hamiltonians is sufficient to make the sequences relative as well. I will denote a sequence of sets of interaction terms for a system S relative to a system S_i as $[\Gamma_S]^{S_i}$. There is a further reason which ensures their relativity, namely the fact that they depend on relative quantum states. As argued at length above, in order to define a sequence of interaction terms from a global Hamiltonian, one has to appeal to quantum states, which, in the context of RQM, are relative to systems. For example, one might want to apply a rule similar to the Non-Interaction Condition to determine the active terms which end up in the sequence $[\Gamma_S]^{S_i}$. Therefore, in general, relative to different systems there will be different sequences of sets of interaction terms for a system.

In addition to that, the arguments I presented in the previous section in the context of absolute states and Hamiltonians demonstrate that which interaction terms end up in the sequence Γ_S depend in particular on the quantum state of S (joint with other systems) . Translated in the context of the ontology of RQM, the terms which end up in $[\Gamma_S]^W$ depend on the quantum state of S (joint with other systems) relative to W.

Therefore, on the premiss that the idea of a global Hamiltonian is sensible, I have demonstrated the three claims I presented at the beginning of this section. Firstly the relativity of the Hamiltonian in RQM. Secondly, sequences of sets of interactions for a system S are relative to other systems. Thirdly, which interactions involving a system S occur relative to a system W depend on the quantum state S (joint with other systems) relative to W. However, as noted in the previous section, one might reject the idea of a global Hamiltonian. Thus it is worth showing that my conclusions do not depend on positing a (possibly naïve) global Hamiltonian.

As I note above, whichever conditions justify the assignment of a certain Hamiltonian to a collection of systems for a given interval of time, they must result in assignments of Hamiltonians in all experimental situations which coincide with the ones assigned in the tested and experimentally verified quantum models. We know that, in the practice of physics, the assignment of quantum models takes into account the quantum sate of the modelled systems. For instance, as I note above, it would be wrong to assign the Hydrogen Hamiltonian to a proton and an electron which have wavefunctions sharply localised on opposite sides of the Earth. However, if they are sufficiently close then it might be appropriate to use a Hydrogen Hamiltonian (although it is not guaranteed: other factors will obviously have an influence on whether it's appropriate or not). The quantum state is relative in RQM, therefore, even if one rejects the idea of a global Hamiltonian, one will find that Hamiltonians must be conceived as relative in RQM.

From the relativity of Hamiltonians, it follows straightforwardly that sequences of interaction terms are relative. Finally, although we have noted that the choice of Hamiltonian for a collection of systems for an interval of time depends on some relative quantum states or relative quantities, it's worth noting that it *surely* depends on the quantum state of the modelled systems. Once again, the example of the electron and proton demonstrates this: the choice of Hamiltonian depends (partially) on the wavefunction *of the electron* and *of the proton*. Thus, the sequence of interaction terms $[\Gamma_S]^W$ depends on the quantum state of S (maybe joint with other systems) relative to W.

Therefore, I have shown that the three claims made at the beginning of this section are true whichever view one has of the Hamiltonian.

5.2.2 Relative Interactions from the dynamics

From the discussion above, one may naturally define a rule to determine the occurrence of interactions:

Relative Interactions from the Dynamics: *Consider three systems S, F and W. Given a partition of time into intervals $\{I_i\}$, define series of interaction terms $[\Gamma_S]^W$ and $[\Gamma_F]^W$. An interaction $[S-F]^W$ between two systems S and F occurs relative to W in the time interval I_0 if and only if there is an interaction term $H_{S\cup F}$ in the set corresponding to interval I_0 in the sequences $[\Gamma_S]^W$ or $[\Gamma_F]^W$.*

where $H_{S\cup F}$ non-separable over the Hilbert spaces $\mathcal{H}_S \otimes \mathcal{H}_F$ of S and F.

Given the relativity of the sequences of interaction terms, the relativity of the occurrence of interactions naturally follows, as it is clear in the formulation of Relative Interactions from the Dynamics above. I have shown above that, whether an interaction term $H_{S\cup F}$ is included in the interaction sequence $[\Gamma_S]^W$ or $[\Gamma_F]^W$ depends on the quantum state of $S \cup F$ relative to W. Evidently, this proposal is affected by the same problem as Interaction as Relative Correlations: it cannot predict the occurrence of interactions (and thus events) involving a system S relative to that same system S. More precisely, Relative Interactions from the Dynamics cannot predicts interactions of the form interactions of the form $[S - F]^S$ and $[S - F]^F$, for any two systems S and F.

It's easy to see the problem. For any system S, the conceptual framework of RQM (see Chapter 2) does not allow for the definition of a quantum state of S relative to S nor of any systems that S is a subsystem of relative to S. Thus, for any two systems S and F, the conceptual framework of RQM (see Chapter 2) implies that neither $|\psi\rangle^{(S)}_{S\cup F}$ (and $\rho^{(S)}_{S\cup F}$) nor $|\psi\rangle^{(F)}_{S\cup F}$ (and $\rho^{(F)}_{S\cup F}$) are defined. I have noted that in order to derive a series of active interaction terms involving S relative to S, one needs to appeal to the quantum state of S (joint with other systems) relative to S, which is not well-defined in RQM.[10] Therefore, for any system S, no series of interaction terms $[\Gamma_S]^S$ for S relative to S can be defined. Therefore, Relative Interactions from the Dynamics cannot predict the occurrence of interactions involving S relative to S. As noted in Chapter 4 when discussing the principle Interactions as Relative Correlations, this is incompatible with the requirements set out in Chapter 3.

[10]Other than, possibly, as a mere computational device, in which case it would always be a fixed state, which wouldn't help.

One might hope the Internal Consistency condition to remedy this situation. Unfortunately, for the same reason as the ones outlined in the case of Interactions as Relative Correlations in Chapter 4, Internal Consistency cannot help. Internal Consistency only applies whenever an interaction involving a system occurs relative to that same system, and the problem we are facing is exactly that such a condition is never realised.

When this problem was encountered in Chapter 4, I noted a *prima facie* solution of positing absolute interactions. At the end of the day, the intuition of "interactions as correlations" had to be discarded nonetheless, but one might hope that positing absolute interactions in this case might solve the problem. I will explore such an avenue in the next section.

5.2.3 Absolute Interactions from the Dynamics

In order to solve the problem of Relative Interactions from the Dynamics, one might want to posit absolute interactions.[11] There is a natural way to define absolute interactions from the formalism developed in this chapter:

Absolute Interactions from the Dynamics: *Consider two distinct systems S, F. Given a partition of time into intervals $\{I_i\}$, define series of interaction terms $[\Gamma_S]^W$ and $[\Gamma_F]^W$ relative to a third distinct system W. An (absolute) interaction $S - F$ between two systems S and F occurs (absolutely) in the time interval I_0 if and only if there is an interaction term $H_{S\cup F}$ in the set corresponding to interval I_0 in the sequences $[\Gamma_S]^W$ or $[\Gamma_F]^W$ for any third distinct system W.*

[11] Exploring the possibility of defining absolute interactions is also important because it is assumed by parts of the literature, notably Adlam and Rovelli (2023).

In other words, an absolute interaction occurs between systems S and F if and only if there is a relevant interaction term in a sequence $[\Gamma_S]^W$ or $[\Gamma_F]^W$ relative to any third system W. Given that interactions are absolute, the problem above does not affect this proposal. Unfortunately I will show that such a proposal is unacceptable.

For one and the same system S there are many sequences of interaction terms relative to different systems $([\Gamma_S]^{W_1},\ [\Gamma_S]^{W_2}, ...)$. According to the proposal under examination, all these sequences denote *absolute* interactions involving S. I argued above that these sequences will be different, in general. Thus, unless we have good reasons to believe otherwise, one cannot expect the resulting pattern of *absolute* events in which a variable takes a value relative to S to form a coherent and empirically adequate picture of the world.

In the case of Absolute Correlations as Interactions, this problem was mitigated because of the interplay of Absolute Correlations as Interactions with Internal Consistency, which enforced coordination among the interactions as predicted from the differing relative quantum states. Unfortunately, I will now show that in the case of Absolute Interactions from the Dynamics, Internal Consistency does not help and the resulting pattern of absolute interactions is unacceptable. In order to do so, I will consider two examples.

Consider the following physical situation. Consider a spin-$\frac{1}{2}$ system S, a spin-z measuring apparatus A, and two spin-x measuring apparatus $B_\uparrow$ and $B_\downarrow$. Suppose there is a $S-A$ interaction in which the spin-z of S becomes determinate. The basic idea is that, relative to A, the $B_\uparrow$ and $B_\downarrow$ apparatus are positioned in such a way that depending on the outcome of the $S-A$

interaction, S will go on to interact with $B_\uparrow$ or $B_\downarrow$. Within RQM, this may be accounted as follows. After the S_A interaction, the quantum state $|\psi\rangle_S^{(A)}$ of S relative to A will be either $|\uparrow, +z\rangle$ or $|\downarrow, -z\rangle$, where the spin-z of the particle has become perfectly entangled with its spatial wavefunction. Then, using a rule similar to the Non-Interaction Rule of Section 5.1.2, one may derive a sequence $[\Gamma_S]^A$. One may assume that the quantum states $|\psi\rangle_{B_\uparrow}^{(A)}$ and $|\psi\rangle_{B_\downarrow}^{(A)}$ of $B_\uparrow$ and $B_\downarrow$ relative to A are such that if the outcome of the $S-A$ interaction is $\uparrow$ and thus if $|\psi\rangle_S^{(A)} = |\uparrow, +z\rangle$, then the sequence $[\Gamma_S]^A$ specifies an interaction with $B_\uparrow$, and viceversa. This will be the case because the interaction $H_{S\cup B_\uparrow}$ (or $H_{S\cup B_\downarrow}$) is not negligible according to the principles set out in Section 5.1.2 if $|\psi\rangle_S^{(A)} = |\uparrow, +z\rangle$ (or $|\psi\rangle_S^{(A)} = |\downarrow, -z\rangle$). Given Absolute Interactions from the Dynamics, whichever of the two interactions occur, it occurs absolutely.

Consider now the situation from the perspective from a third system W. For simplicity, suppose the quantum state of $S-A$ relative to W is pure. Due to Internal Consistency, after the $S-A$ interaction, it will take the form:[12]

$$|\psi\rangle_{S\cup A}^{(W)} = \alpha\,|\uparrow, +z\rangle_S\,|A\uparrow\rangle_A + \beta\,|\downarrow, -z\rangle_S\,|A\downarrow\rangle_A$$

Consider now $[\Gamma_S]^W$. Given the relativity of quantities and quantum states, one might not be able to assume that the situation of S, A, $B_\uparrow$ and $B_\downarrow$ relative to W is roughly similar to the situation of such systems relative to A. The quantum states of $B_\uparrow$ and $B_\downarrow$ relative to W might be such that $[\Gamma_{B_\uparrow}]^W$ and $[\Gamma_{B_\downarrow}]^W$ specify interactions between them and particles of Mars, rather than

[12]Recall that the occurrence of interactions is absolute in the present context.

S. If this were so, one would clearly have to lose any hope in using relative interaction sequences to specify absolute interactions.

However, suppose that the situation relative to W is roughly similar to the situation relative to A, namely that there are two spin-x measuring apparatus $B_\downarrow$ and $B_\uparrow$ positioned in such and such a way relative to A etc... One might hope that under such an assumption sense could be made of Absolute Interactions from the Dynamics. Unfortunately that is not so. I have noted above that the interaction terms $H_{S\cup B_\uparrow}$ or $H_{S\cup B_\downarrow}$ are not negligible according to the principles set out in Section 5.1.2 if the quantum state of S is, respectively, $|\uparrow, +z\rangle$ or $|\downarrow, -z\rangle$. Since the quantum state $|\psi\rangle^{(W)}_{S\cup A}$ after the interaction involves a superposition of terms $|\uparrow, +z\rangle$ and $|\downarrow, -z\rangle$, the interaction series $[\Gamma_S]^{(W)}$ of S relative to W will specify both interactions $S - B_\uparrow$ and $S - B_\uparrow$. According to Absolute Interactions from the Dynamics, such interactions are absolute.

Therefore, from $[\Gamma_S]^W$ one derives that S interacts with both experimental apparata $B_\uparrow$ and $B_\downarrow$. This is evidently implausible. In this example S interacts only with two systems, but it is clear that this type of scenario might be extended to derive approximately contemporaneous[13] interactions with an arbitrary number of spatially separated systems. More importantly, it is clear that if conscious observers are also described by RQM, then one might generalise these kinds of scenarios to derive multiple approximately contemporaneous interactions between a human observer and many spatially separated systems, which would contradict our own experience of the world.

[13]How approximately will depend on how one partitions time into interval, as that is a necessary step to derive a sequence of sets of interaction terms.

Consider the following toy example.

Consider a scientist F performing an experiment with a measuring apparatus A. Suppose that, depending on the outcome of the experiment, the scientist will move to one of two rooms, in which they will interact with another measuring apparatus, respectively, $B_\uparrow$ or $B_\downarrow$. What is assumed is surely possible. Relative to a third observer W, the scientist will be in a superposition, and thus the sequence $[\Gamma_F]^W$ will determine that F interacts with both $B_\uparrow$ and $B_\downarrow$, in contradiction with the (first-person) experience of the scientist.

Hence, even if one appeals to Internal Consistency, Absolute Interactions from the Dynamics is not an adequate principle within the ontology of quantum theory. In addition to that, what these toy examples illustrate is that, more generally, given that which interactions occur may depend on the outcome of previous interactions, if interactions are to be absolute, then outcomes must also be, in some sense, absolute. Although the absoluteness of outcomes does not fit with the original formulations of RQM (Rovell, 1996), it does fit well with the new version of RQM proposed by Adlam and Rovelli (2023), who claim that the relativity of outcomes ought to be understood as relativity of information only.[14] With the absoluteness of outcomes in mind, I will offer one final attempt at offering a specification for the occurrence of interactions in RQM.

[14]'quantum events are no longer observer-dependent in this picture, we cannot say that the event itself is relativized to Alice. But although the event is an absolute, observer-independent fact, it is still correct to say that the value v is relativized to Alice. This is because at this stage Alice is the only observer who has this information about S' (Adlam and Rovelli, 2023, p.11).

5.2.4 Absolute outcomes and interactions

The problem described in the previous section may be characterised as follows: *if what interactions occur depends on the outcome of previous interactions, then outcomes must be absolute*, in some sense. Some traditional avenues to account for this conditional statement in RQM become apparent.

One obvious possibility to account for the conditional statement above is to posit absolute collapse at each interaction. This would evidently lead to a universal, non-relative quantum state, and thus an absolute sequence Γ_S for a system S. This is obviously in contradiction with the main aims of RQM, and therefore must be set aside as an alternative.

Another tempting possibility is to posit many worlds. Consider the example presented above involving a spin-$\frac{1}{2}$ particle S, and three apparata A, $B_\uparrow$ and $B_\downarrow$. One might attempt to resolve the problem by positing that after the $S-A$ interaction, there really are two systems $S_\uparrow$ and $S_\downarrow$ (and two apparata $A_\uparrow$ and $A_\downarrow$), each of which goes on to interact with, respectively, $B_\uparrow$ and $B_\downarrow$. The sequence $[\Gamma_S]^W$ might be understood as referring to both $S_\uparrow$ and $S_\downarrow$, rather than an individual S. In such a theory, in a sense, interactions occur absolutely with absolute outcomes, namely *all* outcomes, but in another sense, which interactions occur is relative to a branch. It is not clear if and how this theory could be developed into an alternative to usual Everettian interpretations[15] but, it's worth noting that, at least compared to positing a global collapse, an evettian account would still allow for a natural notion of relative quantum states (e.g. relative to systems on branches). Nonethless,

[15] See, for instance, Saunders et al. (2010).

since it goes against the main objectives of RQM, I will set it aside.

The only acceptable avenue for RQM is to modify the rule for picking out interactions, in such a way as to allow for absolute interactions without a global collapse or many-worlds. There is a *prima facie* plausible way to do so, and it is worth exploring whether it is satisfactory. Roughly, one might posit that interactions for a system S are derived only from the sequence relative to the last system that S interacted with. In other words, the outcome of the previous interaction is a determining factor for what interaction occurs next. I will call this the Interactions from Absolute Outcomes rule. For instance, consider the example described above, involving a spin-$\frac{1}{2}$ particle S, and three apparatus A, $B_\uparrow$ and $B_\downarrow$. According to the Interactions from Absolute Outcomes rule, after the interaction $S - A$, the only sequence that matters in order to derive the next interaction involving S is $[\Gamma_S]^A$, namely the sequence relative to A. Then, based on which variable the spin of S took relative to A in the $S - A$ interaction, there will be an absolute interaction between S and either $B_\uparrow$ and $B_\downarrow$. However, to maintain the core of RQM intact, one should still insist that there is no global collapse of the quantum state and that relative probabilities are derived via the Relative Born Rule (see Chapter 2). In the present proposal, outcomes are absolute in the sense that they contribute to the determination to which interactions *absolutely* occur.[16]

[16]Note, that *at least prima facie*, this does not imply what Adlam and Rovelli (2023) call cross-perspective links. Namely, consider an interaction between $S - F$ in which a variable $\mathcal{V}$ of S takes a value v relative to F. Consider then a later interaction $F - W$ supposed to represent a measurement of the pointer variable of F which encodes the value v obtained at the $S - F$ interaction. Adlam and Rovelli (2023) assume that W will find out that S obtained the value v, namely the pointer variable of F which takes a value relative to W is the one encoding that the outcome of the $S - F$ interaction is v. On the

I only offered a schemata of a proposal, where the details need to be filled in and many problems need to be addressed. However, this outline is enough to show that the Interactions from Absolute Outcomes rule is doomed.

Consider a Wigner's friend-type scenario. Consider an apparatus F which performs a measurement on a system S in an isolated laboratory, and Wigner W who sits outside of the lab. Suppose that there are two possible outcomes of such a measurement: 1 or 0. Moreover, suppose that the apparatus has been programmed by Wigner in such a way that if the outcome of the experiment were to be 0, then the apparatus would seal the laboratory forever, and if, instead, the outcome were 1, the apparatus would (somehow) communicate the outcome to (and thus interact with) Wigner W, who is outside of the lab.

The Interactions from Absolute Outcomes principle establishes that whether the $F - W$ interaction occurs (absolutely) depends on whether the outcome of the previous $S - F$ interaction is 1 or 0 relative to S. Suppose that the outcome of such interaction relative to S is 1, then the interaction $F - W$ does occur. For simplicity, suppose that the quantum state of $S \cup F$ relative to W is pure. Then, Internal Consistency implies that it is the following:

$$|\psi\rangle^{W}_{F \cup S} = \alpha\,|F,1\rangle_F\,|1\rangle_S + \beta\,|F,0\rangle_F\,|0\rangle_S$$

where $|F,1\rangle$ and $|F,0\rangle$ are the quantum states corresponding to the apparatus showing, respectively, the outcome 1 and 2. Therefore, according to

other hand, I would like to be neutral on this. I would like to be neutral on this. Whether cross-perspective links posited by Adlam and Rovelli (2023) hold or not my argument will be unaffected.

the Relative Born Rule, in the $F - W$ interaction, there will be a non-zero probability that W will witness the apparatus showing the outcome 0. Since the apparatus is programmed to seal the laboratory in case the outcome 0 occurs, W would be left in an inexplicable situation. Therefore, it is not possible that in the $F - W$ interaction the apparatus shows the value 0. If Wigner were to repeat the experiment many times over, he would falsify the Relative Born Rule.

Hence, Interactions from Absolute Outcomes is not adequate to specify the circumstances in which interactions occur.

5.3 Concluding notes

In this chapter I have explored the most natural ways to appeal to the dynamics in the quantum formalism in order to specify the circumstances in which interactions occur in RQM. Unfortunately, no plausible option has been found, which leaves RQM unable to solve the variant of the measurement problem presented in Chapter 3. Given that I have explored and rejected the most natural and plausible options to define the circumstances in which interactions occur, it seems implausible that a principle may be defined which also meets all the aims of RQM. However, if such principle may be found, the arguments towards the end of this chapter suggest that, if the occurrence of interactions is absolute, then the outcome of interactions must also be absolute, in some sense, and a global collapse or many-worlds may need to be introduced.

Although there is no clear solution to the problem of defining the circumstances in which an interaction occurs, it is also worth noting that both the formalism developed in this Chapter, and the Interactions from the Establishment of Entanglement principle do not resolve the question of *which* variable becomes determined at a given interaction, namely the preferred basis problem. I turn to such a problem in the next chapter.

Chapter 6

The preferred basis problem

In chapters 4 and 5 I explored the most plausible ways to specify the circumstances in which interactions occur and concluded that there is no clear way to do so, within the framework of RQM. The analysis in Chapter 4 led us to the belief (shared with Rovelli and his collaborators) that the most appropriate way to specify the occurrence of interactions is to look into the quantum dynamics of the system. I argued that a natural way to do so is to provide a sequence of sets of "active" interaction terms. Unfortunately I concluded that there is no clear way to specify an adequate such sequence. In the present chapter I would like to note a further problem with the approach, namely the preferred basis problem. In brief, *even if* one were able to derive a sequence of sets of interaction terms for a system in a principled way, by itself the sequence does not determine *which* variables become become determinate at the interaction.

Although I have shown that there is no clear way of deriving an adequate sequence of sets of interactions within the framework and fundamental aims of RQM, for the purpose of the arguments in this chapter, I will assume that there is such a sequence. I will consider both possibilities that sequences of sets of interactions $[\Gamma_S]^W$ are relative, and thus the occurrence of interactions is relative, as well as the possibility that an absolute sequence of sets of interactions Γ_S may be derived, and thus the occurrence of interactions is absolute. Under this assumption, I will explore the preferred basis problems and possible solutions to it. Evidently, since no clear way of deriving sequences of interactions is available, the level of detail that can be attained in such exploration of the preferred basis problem will necessarily be limited, and the conclusions only indicative, rather than definitive.

I will begin by presenting the problem in the next section. I will then comment on some of Rovelli's remarks on the problem, which refer to the Hamiltonian for a solution of the issue. Unfortunately, I will note that, without a further criterion, the Hamiltonian on its own will not provide a selection for a preferred basis. More recently, Adlam and Rovelli (2023) acknowledge the problem and appeal to decoherence in order to resolve it. I claim that an appeal to decoherence on its own will not be enough to resolve the problem: what is needed is a rule which selects the preferred variable at each interaction such that, when decoherence sets in, only one variable is selected. Moreover, their willingness to accept multiple variables taking value at one interaction seem to imply even bigger difficulties of ever defining a principled way to derive an interaction, as well as casting doubts on the range of applicability of quantum theory according to RQM. Nonetheless, I explore the possibility that correlations might offer the answer to the preferred basis problem. Although this approach does face some difficulties, at least in the case in which the occurrence of interactions is absolute, there are indications that the difficulties may be overcome.

6.1 The Preferred Basis problem

As noted above, I will assume that sequences of interactions for a system S may be derived in a principled way, either relative sequences $[\Gamma_S]^W$ or absolute sequences Γ_S. When convenient, I will use $[\Gamma_S]^W$ to refer to both relative and absolute sequences.

It's easy to note the preferred basis problem. Consider a sequence of sets of interaction terms $[\Gamma_S]^W$ for a system S (relative to a system W). Such a sequence allows to define a natural non-strict order among interaction terms. Each interaction term denotes an interaction and it has enough structure to denote which systems are interacting, in the following sense. An interaction term with S act as the identity over Hilbert spaces of all non-interacting systems:

$$H_{S\cup F} = H'_{S\cup F} \otimes_{i\neq S,F} \mathbb{1}$$

and is non-separable over the Hilbert spaces of S and F, i.e. $H'_{S\cup F}$ *cannot* be expressed as $H'_S \otimes \mathbb{1} + \mathbb{1} \otimes H'_F$. Thus a sequence $[\Gamma_S]^W$ has the structure to specify which system interacts with which and in what (non-strict) order.

This is not enough. As noted in Chapter 3, in order to recover the predictions of orthodox quantum theory, RQM needs to predict not only which systems interact, but also *which variable* takes on a value at each interaction. In other words, RQM needs to solve the well known problem of the choice of a preferred basis. Without further information, it is not clear how to specify such a preferred basis from the formalism sketched above. Several authors have noted the problem (Lahti and Pellonpää (2023), Muciño et al. (2021, 2022), Healey (2022)).[1] In what follows, I endeavour to evaluate whether a solution can be found in the primary literature or developed independently.

6.2 Rovelli's suggestions

Rovelli has suggested some ways to approach the problem, but unfortunately, he has not provided a detailed solution. The paragraph quoted in the introduction to Chapter 5 is supposed to be a solution. I report it here again:

> 'Which variable takes a value in the interaction is dictated by the physics: in the classical theory, we can describe the interaction between the two systems, say, in terms of an interaction term in the Hamiltonian that depends, in particular, say, on a variable A of the system S: then A is the value that takes value. The reason is that the interaction Hamiltonian depends on the property of S responsible in determining the effect of S on O. And this is precisely how quantum theory describes the world (in RQM): the way systems affects one another.' (Rovelli, 2021, p.3)

Rovelli refers to the fact that the Hamiltonian describing the interaction

[1] Other than noting the issue, Lahti and Pellonpää (2023) have also attempted to develop a solution. They argue that a "measurement scheme" (Lahti and Pellonpää, 2023, p.170-1) is needed to resolve the preferred basis problem. While interesting in its own right, unfortunately such a solution falls short of meeting RQM's fundamental aim not to appeal to measurement, since such a measurement scheme involves a preferring primitively a pointer variable of the apparatus.

‘depends, in particular, say, on a variable A of the system S’ (Rovelli, 2021, p.3) in order to resolve the problem. His thinking appears to be similar in other places:

> ‘In the course of the interaction, the system S affects the system S' . If the effect of the interaction on S' depends on the variable a of S, then the probabilistic spread of a is resolved into an actual value, or, more generally, into an interval I of values in its spectrum.’ (Rovelli, 2018)

Similar remarks can be found elsewhere.[2] As Muciño et al. (2021, pp.9-15, 2022, pp.12-13) note, even though a specific way to express the Hamiltonian may suggest a dependence between particular sets of bases, the Hamiltonian can obviously be re-written in terms of any basis of the relevant Hilbert space.[3] Unless a further criterion is provided, Rovelli's suggestions do not suffice to solve the problem.[4]

6.3 Adlam and Rovelli's suggestion

The recent paper by Adlam and Rovelli (2023) acknowledge the problem:

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[2]See, for instance, Di Biagio and Rovelli (2021, p.3) and Di Biagio and Rovelli (2022, p.5).

[3]For any operator $O : \mathcal{H} \to \mathcal{H}$ with a discrete spectrum and any basis $\{|n\rangle\}$ of $\mathcal{H}$:

$$O = \sum_{n,m} \langle n| O |m\rangle |n\rangle \langle m| = \sum_{n,m} c_{n,m} |n\rangle \langle m|$$

See Messiah (1961, pp.179-196) for the generalisation to continuous spectra.

[4]In Section 6.4 below, I do propose one further criterion based on the Hamiltonian, somewhat inspired by the modal-Hamiltonian interpretation (Lombardi and Castagnino, 2008).

> we can always rewrite an interaction Hamiltonian in a different basis, and a Hamiltonian that looks like it describes a measurement of variable V in one basis will typically look like it describes a measurement of some other variable V' when we write it in a different basis. (Adlam and Rovelli, 2023, p.15)

Adlam and Rovelli dedicate a whole section to comment and resolve the issue. Before analysing Adlam and Rovelli's proposal it is worth noting that they assume that the occurrence of interactions is absolute. Hence, the present section will only be concerned in trying to make sense of their proposal within the context of interactions which occur absolutely.[5]

They consider two (alleged) solutions to this problem, but quickly reject one and favour the other. First, they consider simply stipulating a preferred basis, such as the position basis. According to such a proposal, the position basis would take value at all interactions. They quickly dismiss such a proposal because the preferred basis 'this preferred basis is not evident in the quantum formalism, so this approach seems somewhat ad hoc' (Adlam and Rovelli, 2023, p.15). They are right in rejecting this option: simply *positing* a preferred basis would be a way of positing a hidden variable, which would be against the aims of RQM.

[5]They also assume a further principle which I have only considered briefly in Chapter 5, footnote 16, namely the Cross-Perspective Links principle: 'In a scenario where some observer Alice measures a variable V of a system S, then provided that Alice does not undergo any interactions which destroy the information about V stored in Alice's physical variables, if Bob subsequently measures the physical variable representing Alice's information about the variable V, then Bob's measurement result will match Alice's measurement result.' (Adlam and Rovelli, 2023, p.7). Evidently, the formulation of this principle *presupposes* that the preferred basis problem is solved, since it talks about measurement *of a variable* V on a system S, which clearly assume that the selection of a basis has occurred. As it will become clear, the problems I present below cannot be solved by an appeal to Cross-Perspective Links.

They offer an interesting alternative, according to which multiple variables may take a definite value in an interaction:

> quantum events do not typically have the simple form "variable V taking value v relative to Alice." Rather, they must have a conjunctive form: "variable V_1 taking value v_1 relative to Alice, and variable V_2 taking value v_2 relative to Alice, ..." and so on, specifying definite values for each of the variables singled out by the interaction Hamiltonian in all of the different possible bases for it. The probability distribution over definite values in each disjunct would again be given by the Born rule, and the values in each conjunct would be probabilistically independent. (Adlam and Rovelli, 2023, p.15)

Systems having more than one determined (incompatible) variable[6] might seem counterintuitive, but they argue that it is not problematic in the microscopic realm as there is no need to make conceivable what the experience a qubit enjoyed would be (indeed, there is no such thing). Instead, they argue, the problem of preferred basis needs to be resolved only in cases in which the systems are macroscopic, in order to account for the experience of unique measurement outcomes. This latter problem, they claim, is solved by decoherence:

> 'decoherence effectively selects one variable out of the conjunction of variables that appeared in the original quantum event.

[6]Adlam and Rovelli appeal to this argument in reply to Brukner (2021), who argues that multiple *incompatible* variables become determinate at one interaction. Thus we may conclude that Adlam and Rovelli (2023) intend to allow for multiple incompatible bases to become determinate at one interaction.

It is that variable then which then has a definite value in the perspective of the conscious observer' (Adlam and Rovelli, 2023, p.16)

Adlam and Rovelli's proposal is interesting but it is plagued by severe problems.

Firstly, Adlam and Rovelli's idea that more than one variable may become determinate at one interaction presents a technical puzzle, which was already touched upon in Chapter 3. As explained in Chapter 1, in case of the occurrence of an interaction between two systems F and S, the quantum state $|\psi\rangle_S^{(F)}$ of S relative to F collapses to the eigenstate corresponding to the value taken by a variable in the interaction.[7] For example, suppose S is a spin-$\frac{1}{2}$ system, and suppose that an interaction between F and S relative to F results in the spin-z of S taking the value *up* relative to F. Then the quantum state would collapse to the corresponding eigenstate: $|\psi\rangle_S^{(F)} \rightarrow |\uparrow\rangle$. However, if in that same interaction spin-x also takes a definite value, it is unclear what the quantum state $|\psi\rangle_S^{(F)}$ should be updated to. Therefore, Adlam and Rovelli's proposal would make unclear how to apply RQM from the perspective of system F, as there would not be an unambiguous way to assign a quantum state to S.

This problem might not be fatal, *if* there are no events in which two incompatible variables take a value relative to macroscopic systems such as humans. If this condition holds then, RQM may still explain why scientists are allowed to assign unique and unambiguous quantum states to

[7]Recall that in this section I follow Adlam and Rovelli in assuming that the occurrence of interactions is absolute.

systems when applying quantum theory. However, it would still have significant consequences. Firstly, it may add to the problems for the definition of a specification of what interactions occur. As noted in Chapter 4, which interactions occur may depend on the quantum state. Ambiguity in the assignment of relative quantum state will surely complicate the business of offering an adequate specification of which interactions occur. Secondly, if there is ambiguity in what the appropriate relative quantum states are at a microscopic level, then quantum mechanics may not be applied from the perspective of *all* systems, rather, only from the perspective of macroscopic systems.

Nonetheless, the most important problem is that Adlam and Rovelli's proposal simply does not solve the problem of the preferred basis. In brief, they do not specify how decoherence is supposed to select a unique variable being determined in an interaction. Ultimately, one needs a rule which determines which variables become determinate at each interaction, and then show that in the context of decoherence only one preferred basis takes a value. Adlam and Rovelli lack the first element. To illustrate my point, I will consider the following example. A scientist F measuring the spin of a particle S via an apparatus A. RQM is required to ensure that in the $F-A$ interaction the variable of A that becomes determinate relative to F is the pointer variable corresponding to the bases $|A,\uparrow\rangle$ and $|A,\downarrow\rangle$ only.[8]

Adlam and Rovelli's reasoning seems to go along the following lines. When 'the atom involved interacts with particles on the screen. The in-

[8]Rather than, for instance, the bases $|A,?\rangle = \frac{1}{\sqrt{2}}(|A,\uparrow\rangle+|A,\downarrow\rangle)$ and $|A,!\rangle = \frac{1}{\sqrt{2}}(|A,\uparrow\rangle-|A,\downarrow\rangle)$, which do not correspond to a definite value of the pointer. Other compatible bases may well take a value.

teraction Hamiltonian will not in general single out a unique variable of the atom; therefore, in this interaction, some set of variables of the atom take on definite values relative to the particles in the screen' (Adlam and Rovelli, 2023, p.16) As more and more interactions occur and decoherence kicks in, fewer variables become become determined in the interactions, in such a way that in the $F - A$ interaction, the pointer variable becomes determinate, rather than a variable corresponding to $|A, ?\rangle$ or $|A, !\rangle$.

The reader will be, justifiably, puzzled, because this offers no explanation of why decoherence selects specific variables to become determinate in each interaction. Consider each individual interaction involved in the decoherence process. At each such interaction Adlam and Rovelli claim that the variables that take a value are the ones 'singled out by the interaction Hamiltonian' (Adlam and Rovelli, 2023, p.15). However, as noted in the previous section, without a further criterion, no particular variable is singled out by an interaction Hamiltonian. The only natural conclusion is that at *each* interaction, *all* variables take a value. Then, without further criteria for choosing which variables take a value at an interaction, it is unclear why the onset of decoherence would make any difference.

Adlam and Rovelli's proposal seem to rest on an unstated principle which selects a certain a subset from all the possible variables in each interaction in such a way that, with the onset of decoherence, only the one appropriate variable takes a value. Unfortunately, they do not offer any rule for selection of a variable at an interaction. Therefore, on its own, their reply is not sufficient.[9]

[9]A reader might feel that I have not addressed properly Adlam and Rovelli's focus on

In the next section I will explore some ways in which a rule for a selection of variables may be formulated.

6.4 Interactions as correlations, again

There are a few possibilities to define a rule for the determination of the variable which becomes determinate at one interaction. In this section I will explore a solution that seems most suited to RQM, namely a solution based on correlations.

Before I begin, it's worth noting that a coherent definition of a rule for a selection of a preferred basis is only the first step of what is needed of RQM. It is also necessary to show that the rule selects the right variables. For instance, one needs to be confident that when a measurement is performed, in the interaction between the scientist and the measuring apparatus, not only *a* variable becomes determinate, but in particular that it is the pointer variable which becomes determinate relative to the scientist. In the present thesis, I will only attempt to outline possible ways to define the rule for the determination of variables. I will not attempt to show that they lead to the

information spreading. For instance: 'the dynamical processes involved in decoherence primarily favor the *dissemination of information* in a coarse-graining of the position basis (Wallace 2012), and therefore a significant number of particles in my brain will eventually share the same information about the definite value of the atom in the coarse-grained position basis' (Adlam and Rovelli, 2023, p.16, emphasis mine). Properly addressing and making sense of the talk of information in Adlam and Rovelli's paper is outside of the scope of this thesis. For the purposes of my argument here it's not necessary. Given the basic framework of RQM outlined in Chapter 2, it's indubitable that for RQM to solve the preferred basis problem, RQM needs to determine that in the $F-A$ interaction, the pointer variable of A becomes determinate relative to F. Any talk of how "information" spreads according to RQM must be derived from the formalism, therefore, any way in which talk of information might resolve the problem must ultimately rest on the formalism resolving the problem and, conversely, talk of information spreading cannot resolve the problem unless the formalism itself does.

identification of the correct variables. Such a task can only be attempted if one has an adequate understanding of the circumstances in which interactions happen. As Chapters 4 and 5 show, we do not.

As noted in the previous section, one possibility is to posit a fixed hidden variable, namely a variable which is always determinate at interactions. This option is not compatible with RQM's stated goals. However, there is an option which clearly fits with RQM's spirit, namely an appeal to correlations to define preferred bases. In Chapter 4, I explored whether correlations could be used to define the circumstances in which interactions occur. I concluded that they do not provide enough structure for that. However, the intuition that the perfectly correlated variables are the ones which do take a value seems perfectly suited to the context of the preferred basis problem. Indeed there are other interpretations of quantum theory, namely the modal interpretations which select a preferred variable with the Schmidt decomposition. Hence I will explore if the intuition that correlations select the variables may be coherently applied in RQM.[10]

I start by assuming a step-wise dynamics of the quantum state, namely, I will assume the quantum state is defined at discrete times $\{t_0, t_1, t_2...\}$ and it evolves in between these times. This approximation will be helpful to develop the intuition, but ultimately it ought to be relaxed. Recall that the analysis in the present chapter is predicated on the assumption that, given a partition of time into intervals, a sensible sequence of sets of interactions terms $[\Gamma_S]^W$ for a system S (relative to W) may be derived. Assume that

[10]Note that this intuition may well be what Adlam and Rovelli (2023) have in mind. Indeed they reference Brukner (2021), who assumes that correlations are interactions.

sequences $[\Gamma_S]^W$ are defined using the same partition of time that is used to define the step-wise dynamics, i.e. suppose the interval of time are as follows $]t_0, t_1],]t_1, t_2],]t_2, t_3]$.... Then, natural correlations-based rules for a choice of a preferred basis may be defined, for both cases of the occurrence of interactions being relative and the occurrence of interactions being absolute:

(Relative) From Correlations to Preferred Bases: *For any three systems S, F and W, and an interaction $[S-F]^W$ occurring in the interval of time $]t_n, t_{n+i}]$, if there is a quantum state $|\psi(t_{n+1})\rangle^{(W)}_{S\cup F}$ or $\rho(t_{n+1})^{(W)}_{S\cup F}$ of $S \cup F$ relative to W and such a quantum state predicts a perfect correlation between values of $\mathcal{V}$ and $\mathcal{V}'$, then the following pair of events $[e^{(F)}_S(\mathcal{V})]^W$ and $[e^{(S)}_F(\mathcal{V}')]^W$ occur.*

and:

(Absolute) From Correlations to Preferred Bases: *For any two systems S and F and an interaction $S-F$ occurring in the interval of time $]t_n, t_{n+i}]$, if there is a quantum state $|\psi(t_{n+1})\rangle^{(W)}_{S\cup F}$ or $\rho(t_{n+1})^{(W)}_{S\cup F}$ of $S \cup F$ relative to a third system W and such a quantum state predicts a perfect correlation between values of $\mathcal{V}$ and $\mathcal{V}'$, then the following pair of events $e^{(F)}_S(\mathcal{V})$ and $e^{(S)}_F(\mathcal{V}')$ occur.*

As it was to be expected, the relative version of this principle suffers from similar problems as Interactions as Relative Correlations and Relative Interactions from the Dynamics, namely it cannot deal with interactions of the form $[S-F]^F$, because there is no quantum state of $S \cup F$ relative to F. The absolute version of the principle does not suffer from such a problem but one could worry that due to the relativity of quantum states, it might predict huge variety of preferred bases for each interaction. However, as it was the case for Absolute Interactions as Correlations, Internal Consistency ensures that it is not the case (see Chapter 4). Therefore, I will focus here on the absolute version of the principle above.

Two problems may be immediately identified with using correlations to define the preferred basis. Firstly, as noted in Chapter 4, it may well be the case that the Schmidt decomposition is not unique. For instance, in Chapter 4 it was noted that the singlet state of two spin-$\frac{1}{2}$ particles predicts perfect correlations between different (and incompatible) spin variables. This might seem like the ideal situation in which Adlam and Rovelli's proposal may be applied: if the Schmidt decomposition is not unique, then multiple variables become determinate in the interaction. However, I noted above such a strategy may only be applied in interactions amongst microscopic systems, or, at least, in interactions which do not involve us humans applying quantum theory. However, in principle there does not seem anything wrong with the quantum state of a scientist F and and apparatus A to take the following form relative to a third system:

$$\frac{1}{\sqrt{2}}(|F,0\rangle_F |A,0\rangle_A + |F,1\rangle_F |A,1\rangle_A)$$

Such a quantum state will allow for multiple Schmidt decompositions, because the two Schmidt coefficients are equal. In order to resolve this problem, one might have to argue that quantum states for macroscopic systems never have *exactly* the same Schmidt coefficients.

Secondly, just like in the case of Interactions as the Establishment of

Entanglement, further problems arise once the assumption of a step-wise dynamics is lifted. Indeed, since interactions happen over a certain interval of time, the relative quantum state for the interacting systems $F \cup S$ will change over the time in which the interaction occurs and, with it, the correlations that it predicts. Given the Schmidt decomposition theorem, for any pure quantum state of a bipartite system, there will always be a pair of variables which are perfectly correlated. Therefore, there is a further reasons why correlations face difficulties for predicting a correlation between one pair of variables only for each interaction.

Obviously one may not claim that *all* of the variables that are correlated over the interval of time during which an interaction occurs take a determinate value, because that would mean a continuous spectrum of variables taking a value, even in macroscopic interactions.

Early Rovelli (1997) seems to realise that the Schmidt theorem might be a problem for RQM, but he quickly brushes it off:

> 'given an arbitrary state of the coupled $S - O$ system, there will always be a basis in each of the two Hilbert spaces which gives the bi-orthogonal decomposition [...] But this is of null practical nor theoretical significance. We are interested in certain self-adjoint operators only, representing observables that we know how to measure; for this same reason, we are only interested in correlations between *certain* quantities: the ones we know how to measure.' Rovelli (1997, p.9)

Rovelli claims that we are interested only in quantities that we know how to measure, therefore the fact that all quantum states of bipartite systems admit a Schmidt decomposition is of null theoretical significance. This claim by Rovelli might thus be able to resolve the problem I presented: only correlations between quantities that *are measurable* matter and denote the occurrence of an event. All other correlations may simply be ignored.

This approach would involve an appeal to a primitive notion of *measurable*, in order to define which quantities that may take a value and which correlations matter for the occurrence of an event. As noted by Pienaar (2021) and Muciño et al. (2022), this avenue is obviously incompatible with Rovelli's commitment to eschew any notion of measurement and agents. Hence, this is not an available reply.

Even though Rovelli's approach to the problem does not hit the mark, it seems to me that there are good prospects to resolve the problem. Ultimately, quantum theory might not be able to pick out *exactly* the basis which becomes determinate, just as quantum mechanics might not be able to pick out *exactly* an exact time for the occurrence of an interaction. In Chapter 5 we have discussed some plausible (approximate) conditions to determine whether two systems are interacting. One might hope to use such conditions to pick out an approximate time t at which the interaction ends, and use the quantum state at such a point in order to determine the basis which becomes determined. However, this approach will work only if in a neighbourhood of t which is small relative to the duration of the interaction the correlated basis do change much, relative to the Hilbert space norm. If, instead, within such small neighbourhood the correlated basis significantly changes, it is clear that such a condition may simply not be applied.

6.5 Concluding notes

Even if a sequence of interaction terms (relative or absolute) may be derived for each system (relative to another system), RQM still faces the preferred basis problem. I have shown that suggestions in the primary literature, including Adlam and Rovelli (2023), fail to adequately address the problem. However, ultimately, there might be a way of defining a preferred basis, without an ad hoc postulation, rather by appealing to RQM's focus on correlations, although, the question of whether such a rule selects the appropriate basis is not addressed.

Chapter 7

Conclusion

In the present thesis, I have focused on RQM's problem of measurement. I have argued that current formulations of RQM lack a crucial element for the resolution of such a problem, namely they lack a specification of the circumstances in which interactions occur and what event occurs at each interaction. Moreover, I have shown that the most natural and plausible ways to define such a specification fail, in both the versions of RQM which take the occurrence of events to be absolute and those which take the occurrence of events to be relative. Therefore, I claim that the prospects to articulate a version of RQM which both meets its own goals and resolves the problem of measurement are dim. Interestingly, my arguments indicate that, if the occurrence of events is taken to be absolute, it may be necessary to either introduce a global collapse of the quantum state, or many worlds.

Outside of RQM's measurement problem, this thesis hopefully pushes the literature forward by offering a clean statement of RQM's basic framework, including a discussion of how Internal Consistency is enforced upon the framework, rather than following from the framework, and, more importantly, an analysis of the complexities of defining a dynamics within RQM.

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