Life and Death of Quantum Signals

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1 General context and overview

Information carried by quantum states is at the same time very robust, because it cannot be erased, and very fragile, because it cannot be cloned. As a consequence, it can only be retrieved through statistics performed on a large number of realizations of the quantum state. Moreover, quantum states are heavily affected by their environment and, in many experiments, the system is observed through its imprints within its environment. Those imprints form the quantum signals that ultimately carry the information of interest for the experimentalist. Quantum signals can indeed take many forms, from beams of fundamental particles such as propagating microwave photons in a circuit QED experiment, or a stream of two-level atoms flying across a cavity in cavity-QED experiments. Adopting this signal processing perspective raises the question of the recovery of quantum information carried by these quantum signals.

Answering this question in full generality is a key challenge for quantum technologies. First of all, when signals take the form of a many-particle beam it is not realistic to fully characterize the many-body state of the beam and, as such, to recover the entire signal. It is thus necessary to make a choice and find a representation that is both realistically accessible and gives access to the relevant information. Second, quantum signals are, like their classical counterparts, affected by noise. However, the effect of noise is, in this case, often much more dramatic and leads to the loss of the quantum properties of the signal. Mitigating or controling this mechanism, called decoherence, is thus of key importance.

The questions of the representation and alteration of quantum signals are at the core of my research activities. By adopting a signal processing point of view, it is possible to address the question of the representation for particle beams. A natural way to characterize particle beams is through their correlation functions. In particular, the first correlation function of the field (also known as the Wightman function, Green function, first-order coherence or first-order electronic coherence) gives access to every possible single-mode interferometry experiment and, in the fermionic case, to every possible single-particle interferometry experiment. I worked on two very different types of systems, fermionic and bosonic. I got interested in fermionic beams in the context of electron quantum optics, an emerging field of mesoscopic physics in which it is possible to control electronic states at the single-electron level in a balistic quantum conductor. During my PhD [1], I have reinterpreted the experimentally-accessible quantities as simple transformations of the first-order electronic coherence [2]. This has led to a new way of looking at the experimental tomography of electronic beams, allowing to extract the single-particle wavefunctions emitted by a electron sources [3]. I have also worked on a new decomposition of the first-order electronic coherence, which contains all the single-electron wavefunctions and their occurence probabilities, in terms of elementary single-electron wave functions. This corresponds to decomposing the signal into its “atoms”, that is, the individual electronic wavefunctions carried by it. In this context, the first-order correlator only gives access to single-electron wavefunctions and, in particular, it does not give any information about two-particle entanglement. This is why I also got interested in the study of second-order correlation functions [4, 5].

During my postdoc, I have studied the time-frequency representation of scalar bosonic fields in the context of relativistic quantum field theory. In this context, an observer that is uniformly accelerated is predicted to observe a thermal radiation, an effect called the Unruh effect. The motivation behind my work [6] was to understand how this radiation appears in generic dynamical situations, in which the acceleration varies as a function of time.

Beyond the representation of complex signals and their meaning, I am also interested in the transformation of the signal itself, by its coupling to the environment. This led me to study decoherence for complex systems. In particular, I have studied the decoherence of a single electron in the context of electron quantum optics, when it is interacting with other electrons though effective screened Coulomb interactions [7]. In this case, it is possible to predict how the first-order coherence deforms under such interactions in experimentally-relevant situations [8] and predict which experimental designs are the best suited to fight electronic decoherence [9]. In such a many-body system, the physics of decoherence is really rich but not always easy to understand. In particular, using the tools I have developed, it has been showed that understanding how the quantum information carried by an incoming coherent single-electron excitation is spread over the n-particle excitation sector is quite challenging.

This is why I got interested in effective systems, which are simpler and more controlled such as the ones found in cavity QED. In this case, the decoherence can be carefully engineered and several competing channels can be built (one coming from the photon loss of the high-quality cavity, and the other one coming from the atoms that pass through the cavity). Notably, it is possible to find the states that are the most robust to the action of the environment in this case [10].

Finally, this perspective in terms of signal and information can be used to study more fundamental aspect of the quantum world. In particular, I believe that the emergence of the classical world from a purely quantum perspective is an exciting topic that requires to understand the principles that are at the core of quantum theory. This led me to participate to an ambitious project on the relationships between quantum physics, information theory, and complexity theory. By intertwining these domains, we try to get a wider understanding of the principles and peculiarities of the quantum world. This will result in a two-volume book, the first one being now published [11]. Because it is an important topic, a large part of the book is indeed devoted to the quantum-to-classical transition. The foundations of it have been laid by W.H. Zurek with the introduction of decoherence in which the system transitions from quantum to classical through the unobserved degrees of freedom. This has been later refined with the quantum Darwinism approach that aims at studying the emergent classical consensus between several observers, by using tools from quantum information theory. In this case, the environment is not monolithic like in the standard decoherence approach, but fragmented and each observer has access to a fragment of the environment. Some states, called Darwinian states, have the ability to spread their information across many fragments, and correspond to a classical picture. Yet, many questions remain to clarify, such as the physical meaning of the statistical quantities introduced to analyze the consensus between different observers. This is why I have started an exploratory project which goal is to mix an information theoretic approach based on quantum Shannon theory with the quantum Darwinism framework.

I will review the three topics I am currently working on: the representation of quantum signals (section 2), decoherence of quantum signals (section 3) and finally my work on the emergence of a classical world from quantum signals (section 4). For each of these topics, I will first briefly present the scientific context and the main questions I have adressed, then I will summarize results that are already published and finally, I will briefly describe works still in progress.

2 Representation of quantum signals

My research on quantum signals in electron quantum optics started in 2013. At the time, the foundations of electron quantum optics had been laid down in Ch. Grenier's thesis [12] and were being pushed forward by É. Thibierge [13].

A very important object in the field is the first-order coherence. It was introduced in a similar way to Glauber's first-order coherence in [12]: as an object giving the probability an electrodetector clicks in a weak coupling regime, at first-order in the perturbation theory. From this perspective, the object contains all the single-electron wavefunctions, and their probabilities, carried by the electron beam. This object also received a nice operational interpretation in [14], since it was given the possibility to measure the first-order coherence from current noise measurement. A time-frequency understanding also had just been unraveled using the Wigner function formalism [15].

On the experimental side, the mesoscopic capacitor as an on-demand single-electron source [16] had been studied [17, 18] and the Hanbury Brown and Twiss experiment demonstrated [19]. G. Fève's group was performing the electronic Hong-Ou-Mandel experiment [20]. It is worth noting that the results of both experiments can be predicted from the incoming first-order coherence alone.

However, despite all of these various interpretations of first-order coherence, I was quite dissatisfied by the fundamental interpretation of the object itself. While it was well understood that it contained all the information about single-particle physics, the procedure to extract this information from the signal was not known at the time. That is what motivated me to start a line of research during my PhD with P. Degiovanni at the École normale supérieure de Lyon, that brought concepts from signal processing [21] into electron quantum optics.

I realized during my research fellowship at the European Space Agency that these signal processing techniques could be applied not only to electronic beams, but also to photonic beams. With A. Feller, I started a new research line aiming at bringing a thourough understanding of the field correlators perceived by an accelerating pointlike detector.

2.1 Published works

Electron quantum optics as quantum signal processing [2, 3] Since electronic coherence is a very essential tool, we wanted to have a more general framework to relate this concept to experimental quantities. This led us to make a strong parallel between electron quantum optics and signal processing, considering electronic coherences as "quantum signals" [2]. We have thus reinterpreted electron quantum optics Mach-Zehnder and Franson-like interferometry experiments as linear filtering of first- or second-order electronic coherence. We have also interpreted Hong-Ou-Mandel interferometry as an analog computation of the overlap of two single-electron coherences. Rephrasing these experiments in this way proved to be very fruitful, first of all because it gave a unifying framework and perspective on past, present and forthcoming interferometry experiments. But most interestingly and, I think importantly, it naturally raised the question of the best elementary signals (that we called "electronic atoms of signals") to describe and probe the single electron coherence for a periodically driven system. In [2], we have shown that a natural possibility for these signals are electronic wavefunctions which are orthogonal from one period to the other. Finding such a set of elementary signals would pave the way to have a minimal description of the single-particle excitations emitted by a periodic electronic source. It might also be useful for experiments, since it might lead to more efficient reconstruction protocols suitably tailored for the expected "electronic atoms of signals".

Elaborating over [2], I have thus developped the theoretical framework and a software library that can compute these atoms of signals for first-order electron coherence. Whenever interactions can be neglected, we can use this decomposition in terms of elementary signals to reconstruct the whole many-body state and define a many-body notion of entanglement spectrum which directly leads to an entropic many-body criterion for pure electronic or hole emission. This is in particular relevant when considering a driven Ohmic contact or the mesoscopic capacitor, since this many-body criterion is nothing else than a characterisation of the purity of the source. The software library I have developped is now routinely used by G. Fève's experimental group and this has led to a publication in which the wavefunctions are extracted from the experimental signal in various situations [3]. We are now completing a longer theory-oriented publication describing the method and some of its applications and perspectives.

More prospectively, this analysis might gives us some hints on the road to follow in order to compute the first-order coherence after an interacting region, whatever the source is. This would be a major breakthrough for electron quantum optics since it would enable us to deal with both effects of the Pauli exclusion principle and of the Coulomb interaction even for a complicated many-body initial state.

Noise and second-order electronic coherence [4, 5] In the experiments, the state of the electronic fluid is measured through the average current and current noise. In fact, the relationship between the current noise and the electronic coherence is strong: the true meaning of the Hong-Ou-Mandel experiment is that it enables reconstructing the first-order electronic coherence of an unknown source, given another sufficiently controllable known source, through the measurement of outgoing low-frequency current noise [14, 15].

It is then natural to ask whether there is such a strong relationship involving higher-order electronic coherences. Indeed, it is quite easy to express the current noise in terms of the second-order electronic coherence. In [4], we have shown that it is possible to extract information on the second-order electronic coherence by measuring finite-frequency current correlations in a generalized Franson interferometer.

However, finding an experimentally-accessible scheme to make a full tomography of the second-order electronic coherence for a non-stationary source is still an open problem. The problems are that only low-frequency measurements are feasible now, and that interactions may prevent us to use any extended interferometer for that purpose.

Besides, it can be useful to have a deeper understanding of the noise at the output of a general conductor. In collaboration with I. Safi, we have considered the current noise generated by a dc-biased quantum conductor coupled to other conductors [5]. Within the framework of a perturbative theory based on an initial thermal equilibrium state, we have found that the quantum current noise obeys a fluctuation-dissipation relation that determines it in terms of the average current (dc current–voltage characteristic) even in the presence of strong interactions.

Time-frequency analysis of the Unruh effect [6] In relativistic quantum field theory, the state of a quantum field depends on the observer. This in particular applies to the vacuum, in which an accelerated point-like detector may click. When the detector is uniformly accelerated, the detected radiation is thermal. This effect, called the Unruh effect [22], comes from the spatially-entangled structure of the vacuum. Nonetheless, a uniform acceleration is highly non-physical and it is thus important to understand non-stationary regimes. And a natural quantity to look at, motivated from photodetection theory, is the first-order coherence.

This nonstationarity calls naturally for time-frequency analysis [21] of the first-order correlation function of the fields. While a time-frequency distribution called the Page distribution [23], corresponding to click rates of a single-mode causal detector has been introduced for a few acceleration profiles [24, 25], there was a lack of a general framework in which general movements could be addressed, as well as general states of the field.

In [6], we used the Wigner distribution approach to analyze the content of the field at the level of the detector. This allowed us to address the case of general 1+1d accelerations, for a scalar bosonic field either in the vacuum or in simple quantum states such as multimode coherent states. We analyzed the adiabatic regime, allowing us to give a criterion for the necessary time to build up a thermal radiation. Furthermore, the nonstationarity is also linked to very fundamental problems in quantum field theory. The key observation here is that, except for stationary situations, it is difficult to interpret the signal of the detector in terms of particle content [26, 27]. This can be paraphrased by saying that particles are an emerging notion [28] and not a fundamental concept of quantum field theory. I believe that the time-frequency approach could pave the way to make the link between this emerging notion approach to particles and their standard definition in the many-body approach.

Finally, before the COVID-19 crisis struck, we were expecting an intern, T. Agrenius Gustafsson, to work on the extension of this work to 3+1d motions. Sadly, this has been postponed until further notice. We hope to carry this work forward by the end of the year, though.

2.2 On-going works

Adaptive tomography protocol for electron quantum optics The tomography protocol described in [14], refined and implemented in [3] uses a set of sinusoidal probes to get information about the first-order coherence. However, it is possible to engineer different signals. This immediately raises the question of an optimized protocol that uses the best possible probe from an experimentally-available set. Using techniques from machine learning, such as Bayesian inference, I hope to give an efficient protocol that would offer some speed up over the current tomography protocols. Speeding up tomography protocols would definitely be an enabler for the technological applications foreseen for electron quantum optics platform.

Electron radar With the newly demonstrated ability to perform a tomography and to recover the individual electronic wavefunction [3], electron quantum optics is now mature for applications. One of the most promising direction is electron quantum optics as a quantum metrology platform for solid-state systems. The short timescales involved for electronic pulses (dozens of picoseconds) as well as the sensitivity of individual electrons to their electronic and electromagnetic surroundings makes it a very promising platform for sensing quantum electromagnetic fields as the submicrometer and pico-second time scale.

One idea is to use a Mach-Zehnder interferometer like an electronic radar, using one arm as a reference and the other arm to probe some conductor properties. This naturally leads to a new representation of the first-order coherence called the ambiguity function. I am currently working on this project in collaboration with P. Degiovanni and H. Souquet-Basiège. The theory of the single-electron quantum radar is now almost completed and we are actively working on its applications to experimentally interesting questions within the framework of a simple but quite rich quantum target model.

It is worth noting that this line of research is a part of the SEQUOIA project[1] coordinated by F. Hohls (PTB, Braunschweig) funded within the framework of the EMPIR program of the European Commission.

Atoms of signals in a photonic beam Due to their ubiquitous interaction with their environment, the physics of electronic beams is extremely rich. However, it also implies that harnessing this physics is a very intricate problem. Photons, on the other hand, are easier to control and manipulate. Indeed, this makes them are the platform of choice for communication. Using the lessons learned from electron quantum optics on extracting the atoms from an electron beam, we hope to achieve a similar description in the photonic case. I have started a project with H. Beck and P. Degiovanni on the detection of ultra-low intensity signals. By using the description in terms of atoms of signal, we hope to achieve an efficient adaptive protocol to recover a classical information carried by a weak signal.

Higher-order correlators and the Unruh effect First-order correlators give access to single-detection events. In other words, it gives access to information about all possible single-mode interference effect. While this gives some insights about the properties of the field, it does not allow to conclude about the most quantum feature: entanglement between different modes or, equivalently, different detectors. To understand this, we need to study second-order quantities. Doing so, we will be able to give a proper understanding on how entanglement is affected by the acceleration of the observers.

3 Decoherence of quantum signals

The strangeness of the quantum world in our classical eyes comes from the superposition principle. It is indeed strange because we never experience it directly. The most prominent explaination of this fact, called the quantum-to-classical transition, is indeed the process of decoherence [29]. In our everyday life, we never observe systems directly, but through a very small part of a usually much bigger environment. The spreading of the quantum information to inaccessible degrees of freedom leads to the destruction of interference fringes: quantum superpositions are transformed into classical mixtures. The states of the systems that are able to survive this process and spread their information in the environment without being entangled with it are called the pointer states. These are the emerging classical states of the system. Since decoherence is omnipresent, it is as well of key importance for quantum signals.

I have always found decoherence fascinating. Actually, my research started by studying decoherence in the context of electron quantum optics in 2013, during the internship of my first year of Master with P. Degiovanni, and then during my PhD. In electronic systems, decoherence is indeed very important. Even in the well-controlled situations encountered in electron quantum optics, electrons interact between each other through Coulomb interaction. Predicting how an injected electron deforms and trying to shield against this decoherence is thus a key to understand experimental results.

Despite the success of this work, the complexity of the system, a many-body electronic system, hinders a more fundamental understanding of the decoherence process. This is why during my research fellowship at ESA, I studied simpler, effective systems, like the ones commonly found in cavity QED [30, 31] or their solid-state counterparts in circuit QED [32, 33]. The level of control is now such that it is possible to carefully engineer competing interactions between the system and different environments. This allows to bridge the gap between the idealized situations, with only one decoherence channel, and the tremendous complexity of macroscopic systems.

[1] See `https://www.ptb.de/empir2018/sequoia/project/overview/` for more information.

3.1 Published works

Decoherence and relaxation of a single electron [7, 8, 9] To understand how Coulomb interaction affects the electronic system, it is relevant here to describe the experimental system in more details. In order to guide the electrons, like we do with photons in optical fibers, electron quantum optics uses the edge channels that appears on the edge of a sample in the integer quantum Hall effect. There is an integer number of channels, that behave like chiral 1d wires. The electron is usually injected in one of the channels, and the other channels play the role of the environment. By Coulomb interaction, the injected electron will generate several electron-hole pairs in its channel as well as in the environment. Indeed, this leads to decoherence and relaxation of the incoming electron. From the experimental point of view, it is also possible to engineer the environment, by careful design of the sample. For example, it is possible to loop one of the channels along itself, or to try to shield the sample with gates. These are the key possibilities to control electronic decoherence.

I worked on the problem of the decoherence and relaxation of an arbitrary single-electron excitation on top of the Fermi sea. This problem had already been addressed for the case of energy-resolved single-electron excitations by Ch. Grenier, P. Degiovanni and G. Fève [34]. Although this solves the old problem of the Landau quasi-particle relaxation in chiral quantum Hall edge channel, this work was not sufficient to describe the Hong-Ou-Mandel experiment since energy-resolved excitations have an infinite duration.

It was thus necessary to study the behavior of an arbitrary single-electron excitation in the presence of Coulomb interactions. As was known from previous theoretical [34] and experimental work [35], a non-perturbative treatement of interactions was required since screened Coulomb interactions in these systems lead to the destruction of the electronic quasi-particle in the thermodynamic limit.

In order to address this problem, we have thus relied on the bosonization technique to describe the state of the electronic fluid in terms of bosonic excitations, called edge-magnetoplasmon modes, over vacua which are the Fermi seas at a given chemical potential. In this language, the interaction is simply expressed as an elastic scattering for the edge-magnetoplasmon modes [36, 37]. However, going back and forth between the electronic and bosonic representations of the fluid is non-trivial. Together with C. Cabart, P. Degiovanni and D. Ferraro, we were nevertheless able to derive exact, non-perturbative expressions for the single-electron coherence obtained from an incoming electronic wavepacket on top of the Fermi sea once it comes out of a finite-length interaction region. These analytical formulae did not come out as closed analytical expressions so I developed a multithreaded program that, given some incoming wavefunction and interaction model, numerically computes the first-order coherence. The problem was quite involved numerically, and parallel programming allowed us further numerical exploration.

The fruits of this work can be seen in [7], where we show what happens to an electron that goes through one edge channel of the $\nu = 2$ integer quantum Hall effect, when the two channels are capacitively coupled, and the interaction is short range. This allowed us to understand how the information carried by the incoming excitation is altered by Coulomb interaction. For example, we showed that in the case of the single-electron source used at the Laboratoire Pierre Aigrain, there is almost no traces of the initial energy at which the wavepacket is emitted, after such an interacting region. We interpreted this as a many-body effect that generalizes what happens when a Schrödinger cat state of the electromagnetic field in a cavity QED experiment decoheres [38]. On the other hand, we have identified the recently generated Leviton excitations [39, 40], which are generated by small classical currents, as pointer states [29] with respect to the influence of its electromagnetic environment (here the second edge channel).

It was very exciting to see that the prediction we made on the current noise at the output of a Hong-Ou-Mandel experiment were verified in a joint work with experimentalists [8]. This experimental work tests quantitatively our predictions but also shows the importance of many-body decoherence effects in the $\nu = 2$ edge channel system.

We also have delivered an extensive analysis of electronic decoherence to understand how it is altered when we change the geometry of the sample, the number of channels, or when we add a top gate that screens Coulomb interactions. Even though the current samples using AsGa/AsGaAl semiconductors seem to make an efficient control of decoherence quite challenging for now, we have also shown that the comparatively higher Fermi velocities in graphene could enable such an efficient control [9]. This observation is very timely in the context of the recently demonstrated robust Mach-Zehnder electronic interferometry experiments in graphene [41].

Decoherence with competing environments [10] In the study of decoherence in electron quantum optics, we uncovered the fact that at the many-body level, the pointer states were the Levitons. In this sense, at the many-body level, the interaction between the system and its environment is simple, because we only consider capacitive interaction that act linearly on classical currents. Of course, this simplifying feature is not entirely realistic and in general one should take into account other, non-linear interactions in the current, such as electron tunneling between the different channels. In this case, the two interactions compete with each other, and it is absolutely not trivial to determine the pointer states, if they exist.

However, studying that in a many-body system such as electron quantum optics is a real challenge. This is why I got interested into more controlled systems. This degree of control is achieved in cavity QED, in which a high-fidelity photon cavity interacts with atoms acting as qubits [30]. The qubits act as a controlled environment that is in the end measured, and the photon losses act as an uncontrolled channel. When the coupling of the cavity mode to the atoms is in the dispersive regime, the stream of atoms selects the Fock states. The photon loss, on the other hand, selects the coherent states. As such, except the vacuum, these two decoherence channels do not have common pointer states. In this sense, they are competing environments, trying to access a different information about the system [42].

The presence of two competing environments leads to question the notion of pointer states. We decided to study further this question with A. Feller. We supervised G. Cœuret-Cauquil's Master summer internship on this topic. In the Markovian regime, this dynamics is fully solvable [43] and, beyond the formal solution, we studied the different timescales of the problem. Except in extreme regimes, when one of the two coupling constants is zero, there is no exact pointer state. It is however possible to define approximate pointer states by minimizing the entropy variation of the initial state. Since this problem is involved analytically, I used the Pagmo library [44] to numerically optimize over the states at a given energy. These results can be seen in [10].

3.2 On-going works

Quantum Darwinism in cavity QED Another way to refine decoherence is by introducing a structure in the environment. In most cases the environment is constituted of a lot of subsystems. This refinement allows to ask questions such as the agreement between different observers, having access to different fragments of the environment. Those considerations led Zurek to introduce the notion of quantum Darwinism [45], aiming at explaining the emerging consensus between classical observers. The thesis behind the quantum Darwinism is that the pointer states are able to spread out their information the best in the different environment fragments.

During the second part of G. Coeuret Cauquil's internship, we adapted this notion to the case of a Markovian dynamics having a pointer state. This work will lead to a publication in 2020.

4 A world of quantum signals

To me, quantum theory is a fascinating topic in itself. I should stress the word "theory" here. Because it has sparkled research and results in communication theory [46], computer science [47] and even pure mathematics [48], quantum theory goes well beyond "mechanics". This crossfertilization between the different disciplines, as well as the variety of approach have, I believe, given a new understanding of quantum theory, separating some of the key principles from the mathematical complexity.

This interest has led me to cowrite a book, in French, on the relationships between quantum physics, communication theory, and computer science. In the end, it will result in two volumes, each weighing 400 to 500 pages. The first of them is now published [11]. One of the byproducts of this long-term project is an exploratory research project which aims at connecting quantum Darwinism to quantum Shannon theory, the natural framework for quantum communication performance assessment. We hope to give a deeper understanding of quantum Darwinism by expanding it into a more general framework based on an operational formulation of quantum observation in terms of quantum communication protocols and quantum information quantities.

4.1 Published works

Quantum physics, information theory and computer science [11] During my Bachelor, N. Portier and P. Degiovanni gave a course on the relations between computer science, information theory and quantum mechanics. Because of my strong interest in computer science (especially foundations and complexity theory), I found it was very interesting to follow, even though quite cryptic, at that time. I had the chance to discuss furthermore of the content of the course with them, along with two other students, C. Cabart and A. Feller, who were preparing their PhDs in the same departement. All together, we started to work on a book project based on the content of this course, that we have extended beyond its original scope. In this book, we review the enhancements to communication and computation that are allowed by quantum mechanics, as well as the fundamental limitations it imposes.

The first volume [11] is now published. It gives an introduction to the three domains, as well as the quantum counterpart of information theory and complexity theory. The last chapters are dedicated to the dynamics of open quantum systems from the quantum trajectory point of view and finally to the discussion of entanglement in quantum mechanics and the Bell experiments. My main contributions are on the computer science parts and on the dynamics of open quantum systems. I wrote a chapter on the foundations of computer science and the computational complexity theory, both classical and quantum. I was also involved in the chapters about quantum trajectories for realistic systems, like cavity QED and circuit QED experiments.

We are now writing the second volume, that will focus more on the fundamental concepts introduced by quantum mechanics. Inspired by [49], I am writing a short introduction to what we could expect from a physical theory based on probability. The goal of this second volume is to shed some light on the nature of quantum mechanics. Can it be used to describe the whole physical world? What would it imply? Combining and relating quantum mechanics to information theory and computational complexity theory, we highlight that the framework in which quantum mechanics seems the most natural is the one in which the quantum state of the system is not objective as pointed out by N. Bohr, but rather relative to the observer and its capabilities, as originally stated precisely by H. Everett [50], or more recently rediscovered by C. Rovelli [51] or A. Auffèves and P. Grangier [52]. Furthermore, the constraints on the very nature of quantum mechanics lead us to explain the emergence of a classical world from a quantum universe. In the end, we draw a parallel between general relativity, where space and time are relative to an observer, and quantum mechanics. We will conclude this two-volume book by discussing some of the conceptual issues behind the marriage between quantum mechanics and general relativity.

4.2 On-going works

Quantum Shannon theory and quantum Darwinism The writing of the second volume gave rise to a question related to quantum Darwinism: how can we relate the observations made by different observers? The way to solve this in quantum Darwinism is by introducing information-theoretic quantities that measure, in some sense, the degree of consensus between different observers. However, because they are statistical, these quantities are difficult to interpret without further operational framework. The advent of quantum communication theory [46] was to provide protocols that connect these statistical quantities to operational protocols.

Inside ESA, it is possible to fund exploratory projects through a programme called Ariadna. We started a 30 000 € project with O. Fawzi, I. Frérot and P. Degiovanni, the goal being to translate the notions introduced in quantum Darwinism and its refinements into operational terms. This will give us an understanding of the capabilities of quantum observers sharing a quantum state beyond the mathematical quantities.

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