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Interpreting Quantum Mechanics

Sujeevan Sivasundaram

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Centre for Science Studies, University of Aarhus, Denmark
Research group: History and philosophy of science

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Interpreting Quantum Mechanics

Candidate: Sujeevan Sivasundaram 20071433

Supervisor: Kristian Hvidtfelt Nielsen

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Institute of Physics and Astronomy
Aarhus University

Abstract

Kvantemekanik er en teori, der næsten har eksisteret i 100 år. Alligevel er der stadigt spørgsmål ift. fortolkningen samt selve teoriens fundament. I de senere år har der været en øget opmærksomhed omkring disse problemstillinger, hvilket har medført en opblomstring af undersøgelser af de forskellige fortolkninger af kvantemekanikken og deres popularitet. En undersøgelse af en sådan natur, er netop det der er blevet foretaget i dette speciale. 1234 spørgeskemaer blev sendt ud med mail hvor 150 personer svarede. Spørgsmålene omhandlede forskellige fortolkninger af kvantemekanik, og forskellige problemstillinger i kvantemekanikken. Svarene viser at Københavnerfortolkningen stadig er den mest populære fortolkning af kvantemekanik, men også at den fortolkning som fysikere betragter som Københavnerfortolkningen, ikke stemmer overens med Bohr og Heisenbergs oprindelige tanker. Yderligere afslørede undersøgelsen, at fysikere ser fortolkningsspørgsmålet af fysiske teorier som et vigtig element, men fordi eksperimenter ikke kan benyttes til at skelne de forskellge fortolkninger fra hinanden, fastholder de sig på den etablerede fortolkning.

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I would also like to thank Klaus Mølmer for the guidance and support he has provided, whether it be suggesting my supervisor or in getting me more participants for my survey. Talking to you concerning quantum foundations has been one of the most enjoyable parts of this process, this was especially highlighted by your enthusiasm, which is admirable and contagious. It is best described by the first time I came to you to talk about interpretations. I clearly recall uttering the words "interpretations of quantum mechanics" and you went off talking about the subject for half an hour, finishing with "I don't know if that answered your question" even though I never got to ask my question.

A thank you should also be given to Magnus Johan Aarslev, Daniel Østergaard Andreasen and Mehmet Serdar Yilmaz for helping me test the survey, Brian Julsgaard for helping me clarify some features of quantum mechanics and of course to all those who participated in the survey. Without your participation none of the following would have been of much use.

Contents

Chapter 1

Introduction

Quantum mechanics is the most well-corroborated theory in physics. The formalism of quantum mechanics does, however, not lend itself easily to interpretation. The Bohr-Einstein debates highlight some of the difficulties in accepting quantum mechanics, and in the recent past it seems as if the attention to the questions concerning the foundations have once more come to the fore [1]. That these questions still linger almost a hundred years after the conception of quantum mechanics shows how novel and counterintuitive some of its features are. It also represents some discontent with the Copenhagen interpretation. These questions concerning quantum mechanics and the standard interpretation will be explored in this thesis. It will attempt to give a representative overview of the opinions and attitudes of physicist concerning the foundations and interpretations of quantum mechanics. Today there are a number of alternative interpretations of quantum mechanics to the standard Copenhagen interpretation, each handling, in their own mind, unsatisfactory features of the theory or the application of it. These multiple interpretations make physicists face the question of which is the right one? How can this be decided, when measurements cannot separate the different interpretations? One answer could simply be not to face it, as long as experiments cannot be used to distinguish the interpretations. That is the agnostic answer, but how prevalent is this answer among physicists? The answers to such questions are to be found through a survey. Such a survey was completed by posing a number of questions to physicist. The questions concerned the foundations and interpretations of quantum mechanics as well as theories and interpretations in general. It was inspired by a survey carried out by Maximillian Schlosshauer [2]. 150 physicist participated in the survey, which makes its sample size significantly larger than other surveys of this nature, including that of Schlosshauer [40] [41] [42].

The analysis of physicists' attitudes and opinions concerning these topics, plays a central role in evaluating and understanding how we do physics today. Are we open to different views on the same formalism or are we ingrained in the notion that there is and can only be one answer in physics? A notion that separates the sciences from the humanities.

In this thesis a brief description of quantum mechanics will be given, presenting some of its special features as well as some of its problems. This will be followed by presentations of three different interpretations, highlighting the different approaches they take in interpreting quantum mechanics and solving some of its problems. The three interpretations are the Copenhagen interpretation, the many worlds interpretation and bohmian mechanics. These three have been chosen since they display distinct features from one another and are the three oldest interpretations. Quantum bayesianism, and the objective collapse theory of Ghihardi, Rimini and Weber represent different routes in interpreting quantum mechanics than those focused upon here. These were omitted from focus since the number of interpretations would not fit the scope of the thesis. It is worth stressing that in the presentations of quantum mechanics and the three interpretations, the objective is not to explain the historical development of the different formalisms, but rather to focus on the formalisms themselves and what they imply. This does not mean that historical context will be completely omitted, since some things are more easily understood in this context. Further in elucidating the different interpretations, the attention will be directed to the original thoughts of its creators, not what is necessarily associated with it by the physics community in general. These presentations will attempt to emphasize the various appeals of the interpretations, and what values it implies a physical theory should have. These presentations will be followed by a comparison of the three interpretations and very brief descriptions of other interpretations. All of the preceding presentations serve the purpose of framing the survey which was carried out. A description and an account of the survey is given, going through each question and the respective answers to each question. The answers are analyzed and explanations in the context of the various interpretations are given. Demographical tendencies are explored, for those demographics that were deemed to have a large enough sample size, to be considered representative. Finally certain correlations in the survey are explored and the perspectives of the survey are drawn.

A small note on the word interpretation. An interpretation relates to how one interprets a given formalism in physics. Different interpretations should therefore apply to the same formalism. This is strictly speaking not the case, when the word interpretation is applied here. The interpretations that will be encountered are distinct theories from one another, their structure is different. However, they all produce the same results and are therefore said to be different interpretations of the same formalism, namely that of quantum mechanics in our case.

"*This problem of getting the interpretation proved to be rather more difficult than just working out the equation*" Paul Dirac [19, p 1]

Chapter 2

Introduction to Quantum Mechanics

This section serves as a brief summary of the formalism and features of quantum mechanics, highlighting some of its departures from classical physics and some of the concerns that were raised in the aftermath of its conception. The concept of decoherence is also described, since it plays a central role in some of the interpretations.

1 Formalism

1.1 Hilbert Space

Systems in quantum mechanics are described by their *wave function.* In standard quantum mechanics the description prescribed by the wave function is complete, it describes all aspects of the system. In general wave functions are complex valued and are dependent on a phase space coordinate[1] q. All wave functions satisfy the property of normalization, i.e.

$$\int |\Psi(q)|^2 dq = 1, \tag{2.1}$$

where the integral is taken over all phase space. The wave functions dependence on q will in general be suppressed in the notation from now on, unless it serves a purpose. If the integral of a function's square modulus is finite, over its domain, then the functions are said to be normalizable, since $\int |f(x)|^2 dx = N \Leftrightarrow \int \left|\frac{f(x)}{N}\right|^2 dx = 1$, where N is finite. Therefore, all normalizable function are of interest, because they can easily be made to accommodate (2.1). In quantum mechanics the wave function can be regarded as a vector. According to this picture all mathematical functions can be thought of as comprising a vector space. A part of this vector space composes the space of wave functions, i.e. normalizable functions. This space is called a Hilbert space $\mathcal{H}$ after the mathematician David Hilbert[2]. An inner product is associated with a Hilbert space; take two functions Ψ_1 and Ψ_2 in the Hilbert space $\mathcal{H}$, the inner product between them is defined as

$$< \Psi_1 | \Psi_2 > \equiv \int \Psi_1^* \Psi_2 dq. \tag{2.2}$$

[1] It can depend on an arbitrary number of coordinates

[2] There is not one Hilbert space but many, depending on the dimensionality of the wave function among other things.

Since both functions reside in the Hilbert space, they are normalizable and the inner product is guaranteed to exist [3]. The Hilbert space, $\mathcal{H}$, is an inner product space and can be spanned by a complete set of functions $\{\varphi_i\}$ [3]. This means that any function in the Hilbert space, $\mathcal{H}$, can be expressed as a linear combination of these functions, which is termed a superposition in physics. Any wave function in $\mathcal{H}$ can therefore be expressed as

$$\Psi = \sum_{i=1}^{N} C_i \varphi_i, \tag{2.3}$$

where c_i is the coefficient of the i'th term, and N is the dimensionality of the Hilbert space, which can be either finite or infinite. The functions spanning a Hilbert space, $\mathcal{H}$, are mutually orthogonal and can easily be made orthonormal by multiplying the various functions with appropriate constants so that

$$< \phi_i | \phi_j >= \delta_{ij}. \tag{2.4}$$

So far, no meaning has been attached to the value of the wave function. This is done through the *Born rule* named after German physicist Max Born, which states that the square amplitude of the wave function $|\Psi(q)|^2$ relates to the probability of finding the system in the coordinate q of phase space. Therefore, the normalization condition (2.1) says that the probability of finding the particle anywhere in the phase space is unity [3].

1.2 The Schrödinger Equation

The evolution of the wave function is governed by Erwin Schrödinger's famous equation

$$\frac{-\hbar^2}{2m} \frac{\partial^2 \Psi}{\partial x^2} + V\Psi = i\hbar \frac{\partial \Psi}{\partial t}, \tag{2.5}$$

where V is the potential of the system and $\hbar$ is Planck's constant divided by 2π. In the case that the potential does not depend on time, the wave function can be separated into two functions, one dependent on time and another on space

$$\Psi(x,t) = \psi(x)\varphi(t). \tag{2.6}$$

In this case, it can be shown that the time-dependent function will always equal $\varphi(t) = \exp\left(-i\frac{Et}{\hbar}\right)$. Because of this, one is often only interested in the space-dependent function. Rewriting the Schrödinger equation (2.5) for the space-dependent function, one finds the stationary Schrödinger equation

$$-\frac{\hbar^2}{2m} \frac{d^2\psi}{dx^2} + V\psi = E\psi. \tag{2.7}$$

Often one is only concerned about finding ψ, since from it Ψ can easily be found by $\Psi = \psi \exp\left(-i\frac{Et}{\hbar}\right)$. The stationary Schrödinger equation is just an eigenvalue equation, which will be touched upon next.

1.3 Observables

A radical departure from classical mechanics is that in quantum mechanics observables O are not mathematical quantities, but are mathematical operators, such as $\frac{d}{dq}$. These operators each have their own eigenfunctions, or rather eigenstates ϕ_i

$$O\phi_i = o_i\phi_i, \tag{2.8}$$

where o_i is the eigenvalue relating to the eigenstate, ϕ_i. These eigenstates are also called determinate states, since a system in this state, ϕ_i, would always yield the same outcome of measurement of the observable O, specifically the eigenvalue o_i. Since the wave function can have a complex value, an operator can have complex eigenvalues. To ensure real eigenvalues, a restriction is imposed on the operators which can represent physical observables: Operators representing physical observables must be hermitian

$$O = O^*. \tag{2.9}$$

This restriction can be shown to ensure that the eigenvalues of observables will always be real [3]. Different eigenstates can have the same eigenvalue, which is termed *degenerancy*. When this is not the case, that is when all the eigenstates have distinct eigenvalues, then it can be shown that the eigenstates will be mutually orthogonal. In general, a state of a system is not in a determinate state, but the eigenstates of an observable form a complete set of functions spanning a subspace of the Hilbert space, where the state of the system must be in. Therefore, the wave function of a system can always be expressed as a superposition of the eigenstates of an observable, by the decomposition described in (2.3) and holds for all times. The determinate states are not time dependent, however, the coefficients are. In the proceeding of the thesis coefficients written in capital letters correspond to time dependent coefficient, while lowercase letters correspond to time independent coefficients. The decomposition of the wave function into determinate states of an observable is not unique, as another superposition with eigenstates, relating to another observable, can represent the same state. Indeed, this point is important, because it relates to the way we specify wave functions, or physical states. The specification of these are not unique, and the different representation depend on which basis one chooses to express the state. This fact makes quantum mechanics radically different from classical mechanics. Furthermore, in general, the state of a system is not in a determinate state, as in classical mechanics, however, it can always be expressed as a superposition of determinate states. Quantum mechanics does not provide one with a definite result, only the probability of obtaining different results. When one performs a measurement of a specific observable on a system, the possible outcomes are the eigenvalues of the observable. The probability of obtaining a specific eigenvalue is given as the square modulus of the coefficient of the term containing the eigenfunction corresponding to the obtained eigenvalue in the decomposition of the wave function into determinate states of the observable. The term *expectation value* is introduced in quantum mechanics, which is the mean[3] value of possible outcomes weighted according to the probability. Regard the observable O, its expectation value $< O >$ for the system represented by the wave function ψ is given by

$$< O > = < \psi | O\psi > = \int \psi^* O \psi dq. \tag{2.10}$$

Examples of observables are those relating to position and momentum, which are given by

$$x = x \cdot \qquad p = -i\hbar\frac{\partial}{\partial x} \tag{2.11}$$

[3]Note it is not the most probable value

where $\hbar$ is Planck's constant divided by 2π. The position operator is to multiply the wave function with the position x, while the momentum operator is to differentiate with respect to x and multiply by $i\hbar$. It is readily verified that these observables are hermitian. Other observables can be constructed from the definition of these [3]. In the picture where wave functions are vectors, the operators can be represented by matrices.

1.4 The Uncertainty Principle

The deviation from the mean, i.e. the expectation value, of an observable A is characterized by σ through

$$\sigma_A^2 =< (A- < A >)\Psi|(A- < A >)\Psi >, \tag{2.12}$$

This can be shown to imply

$$\sigma_A \sigma_B \geq -\frac{i}{2} < [A, B] > . \tag{2.13}$$

This is the general version of Werner Heisenberg's uncertainty principle, which states that it is not in general possible to know two observables to infinite precision [3], yet another radical break from classical mechanics. This feature arises from the fact that one can specify a system in multiple ways. The determinate states of A and B respectively, span the Hilbert space. Every wave function can be expressed as a linear combination of the determinate states of A or the determinate states of B. If A and B do not commute, they do not have the same determinate states. A determinate state of A can never equal a determinate state of B. One is faced with an irreducible indeterminacy.

Using the operators for momentum and position, one sees that (2.13) becomes

$$\sigma_x \sigma_p \geq \frac{\hbar}{2}. \tag{2.14}$$

1.5 Composite system

The previous states have all been states of one system, however, often two systems can interact and the need to handle composite systems arises. Regard a composite system, T, composed of two systems S_1 and S_2. The state of each system S_1 and S_2 reside in their respective Hilbert spaces $\mathcal{H}_{S_1}$, spanned by $\{\varphi_i\}$, and $\mathcal{H}_{S_2}$, spanned by $\{\phi_i\}$. Operators defined on $\mathcal{H}_{S_1}$ do not act on elements of $\mathcal{H}_{S_2}$ and vice versa. To give these operators meaning when applied to the composite system, the Hilbert space of the composite system must be expressed as a direct product of the two Hilbert spaces

$$\mathcal{H}_T = \mathcal{H}_{S_1} \otimes \mathcal{H}_{S_2}. \tag{2.15}$$

This means that the state of the composite system, T, can in general be expressed as

$$\psi^T = \sum_{i,j} a_{ij} \phi_i \varphi_j. \tag{2.16}$$

This expression of composite systems plays a central role when the observer or apparatus is regarded as quantum system interacting with the system of interest [7].

1.6 Schrödinger's Cat and the Measurement Problem

Though quantum mechanics is a highly successful theory in terms of its predicting power, several paradoxes are associated with the theory. The most famous paradox is probably that of Schrödinger's cat which is a specific example of the so-called *measurement problem.* Schrödinger envisaged a cat locked in a box. In this box there is a radioactive nucleus which is coupled to a device, that triggers a poison in the box of the cat, when the nucleon decays. This poison would kill the cat. According to quantum mechanics, this nucleus is in a superposition of a decayed state and a non-decayed state. When the system consisting of box, cat and radioactive nucleus is left to itself, the nucleus will be in a superposition of decayed and non-decayed state, the poison will therefore also be in a superposition of a triggered and non-triggered state, so the cat must be in a superposition of a dead- and an alive state, which seems absurd [3]. This paradox is a particular instance of the measurement problem. The measurement problem relates to the fact that the formalism of quantum mechanics shows that in general a system will be in a superposition of determinate states of an observable, but we never observe superpositions in reality. A further complicating element regarding measurements in quantum mechanics, is the question of why the system and interacting measuring device decompose to the states corresponding to eigenstates of the observable and the apparatus states, instead of any other decomposition? This decomposition could happen in a variety of ways. This element can be thought of as a part of the measurement problem, but it also has a name of its own, *the problem of preferred basis.* However, this problem has been solved by the development of decoherence [8], which will be presented in the next section.

1.7 Decoherence

The concept of decoherence concerns the boundary between the classical- and the quantum realm. It plays a central role in several interpretations and solves some of the problems concerning measurement, namely the problem of preferred basis, but it does not solve the measurement problem. Decoherence has only gathered significant attention the last 30 years, therefore old interpretations such as the Copenhagen interpretation and many-worlds interpretation, did not use the concept in their original formulation[4]. Decoherence is not a concept added to the formalism of quantum mechanics, but a consequence of it. Decoherence arises when a system interacts with the environment, or a system with many degrees of freedom. Regard a system S and an apparatus A. When the apparatus measures the system, it is interacting with it. The apparatus relates to the observable Q, with the eigenstates $\{\varphi_i\}$ so the system S can be expressed as a superposition of these eigenstates. A can be considered to be in a ready state η before the measurement takes place, therefore

$$\psi^{S+A} = \eta \sum_i c_i \varphi_i. \tag{2.17}$$

where c_i are the coefficients of the superposition. To see what happens next, a time dependent picture is taken [8].

Because of the interaction between the system and apparatus the wave function changes to

[4] Original formulation might be somewhat misleading, when it comes to the Copenhagen interpretation, since it implies that there is one unified view of what it represents.

$$\Psi^{S+A} = \sum_i C_i \varphi_i \eta(\mathbf{y} - \lambda Q_i t), \tag{2.18}$$

where λ characterizes the strength of the interaction and the time dependence is expressed in the coefficients. When the time Δt has passed the interaction is over, and the final wave function becomes

$$\psi_f^{S+A} = \sum_i C_i \varphi_i \eta(\mathbf{y} - \lambda Q_i \Delta t). \tag{2.19}$$

If the interaction is strong enough to uphold the inequality

$$\lambda Q_i \Delta t >> 1, \tag{2.20}$$

then the apparatus can be described as having different functions η_i corresponding to specific eigenvalues, i.e. different observed results, called *pointer states.* These different functions, describing the apparatus, are given by

$$\eta_i = \eta(\mathbf{y} - \lambda Q_i \Delta t), \tag{2.21}$$

so the composite wave function can be expressed as

$$\psi^{S+A} = \sum_i c_i \eta_i \varphi_i. \tag{2.22}$$

The pointer states, η_i, are not necessarily orthogonal to one another, and interference between the terms is possible. Interference behaviour is a quantum phenomenon, and when it is absent one is left with a system that behaves classically.

Systems are never completely isolated when measurements are performed on the system[5], so they interact with the environment E. Before the measurement the environment is in the state ε, however, after it interacts with the composite system $S + A$, it to can be thought as being in a superposition of pointer states as well

$$\psi^{S+A+E} = \varepsilon \sum_i \eta_i \varphi_i \underset{\text{interaction}}{\rightarrow} \psi^{S+A+E} = \sum_i \eta_i \varphi_i \varepsilon_i. \tag{2.23}$$

The interaction with the environment causes the system $S + A$ to decohere, that is it suppresses the interference in (2.22) by making the pointer states η_i orthogonal. This cannot in general be shown to apply for all quantum systems, interacting with the environment, but has been shown for a multitude of quantum systems. The interference is not lost, but is leaked into the environment through the states ϵ_i, which we do not observe. Decoherence chooses a preferred basis, namely the pointer basis. However, decoherence only ensures that these terms are orthogonal, and does not remove the superposition, it therefore does not solve the measurement problem. The time scale of decoherence, or the suppressing of interference is extremely short, so that for most purposes it can be taken to happen instantaneously. Decoherence explains why we do not observe interference effects on the macroscopic scale. The concept has also played a central role in developing new interpretations such as consistent histories, and elucidating some features of already existing interpretations [8] [7].

[5]The exception being the whole Universe.

Chapter 3

The Copenhagen Interpretation

The Copenhagen interpretation of quantum mechanics is widely recognized as the established and most popular interpretation of quantum mechanics. The founders of the interpretation are largely considered to be Niels Bohr and Werner Heisenberg. The interpretation was the first interpretation of quantum mechanics, but like quantum mechanics it did not come to existence in a single instance, but accreted concepts and notions over time. It is a collection of thoughts concerning quantum mechanics, from the minds of Bohr, Heisenberg, Born, Von Neumann and more. When the term "The Copenhagen interpretation" was first used, it was presented as if it was a coherent collection of thoughts. However, the literature from these physicists, concerning some of the very notions in the interpretation, show that they had different understandings of how to interpret various elements of the theory [43]. This makes some parts of the interpretation unclear and vague, and it has even been claimed, that there is not one Copenhagen interpretation, but one for each individual adhering to the interpretation [43]. The term "Copenhagen interpretation" refers to the group of physicists surrounding Bohr in Copenhagen, but Borh himself never used the term. Heisenberg uses the term in his book "Physics and Philosophy", but mostly the term was used by deterrents of the interpretation. The Copenhagen interpretation does not refer to one body of work or one person's thoughts that have been elaborated or interpreted by others. This stems from the fact that quantum mechanics was developed at quite a fast pace and not by one physicist but multiple. This made the theory precede its own interpretation; the physicists had created a mathematical formalism that was able to predict the outcomes of experiments, but interpreting this formalism in terms of the underlying physical processes was not easily done. The thoughts of the aforementioned physicists, and therefore the conception of the Copenhagen interpretation came under, and in the aftermath, of the conception of quantum mechanics. To exacerbate the ambiguity relating to the Copenhagen interpretation, Bohr is notorious for being rather turbid and dense in his writing, making it difficult to understand what his exact thoughts were.

All this makes it difficult to answer the question "What exactly is the Copenhagen interpretation?"[1]. Most would agree to some central concepts that are associated with the Copenhagen interpretation, an assumption that will be tested by the survey. The exact understanding of each concept, however, may differ. This section provides an insight into these concepts and will attempt to highlight some of the different understandings of them. Because the conception of the Copenhagen interpretation is spread over a time period it

[1]It also makes the interpretation quite intriguing from a historical point of view, and a great deal of literature has been written about the subject.

relates to the thoughts of multiple physicists. For these reasons the presentation given here has more of a historic perspective than the others.

1 The Correspondence Principle

The correspondence principle was a doctrine of Bohr's, which played a fundamental role in Bohr's thoughts concerning and developing quantum mechanics. The principle, like much in the Copenhagen interpretation, does not lend itself easily to a straightforward explanation. Indeed, Bohr was allegedly agitated that one of his own students and collaborators Léon Rosenfeld did not fully grasp the principle [16, p 690]. What most of the physics community today consider the correspondence principle is not in line with what Bohr considered the correspondence principle to be [14] [44]. A vague, but all inclusive, description would be that the correspondence principle relates to the link between quantum mechanics and classical mechanics. To elucidate what was, or is, meant by the correspondence principle, the principle will be used to derive different quantum features, in some of the following sections.

1.1 The Asymptotic Relation

One version of the principle, the asymptotic relation, says that quantum mechanics must produce the same predictions as classical mechanics in the classical limit, i.e. large quantum numbers. This version is arguably the established, or at least most used, version of the principle [14] [43].

However, Heisenberg reveals that classical physics does not only serve a role in the limit. One needs the concept of classical physics to form the language of quantum mechanics [9, chapter 3]. Bohr thought of the correspondence principle as a law of the quantum theory and that quantum mechanics is a generalization of classical mechanics.

> *..this Correspondence Principle must be regarded purely as a law of the quantum theory, which can in no way diminish the contrast between the postulates and electrodynamic theory.* [12]

The quote shows that the correspondence principle is not the mere asymptotic relation often quoted. Bohr used the principle in his work relating to the old quantum theory, which was a mixture of classical physics and new quantum principles. In Bohr's article describing his model of the atom, Bohr succeeds in deriving Balmer's formula and even in giving a description of the Rydberg constant in terms of natural constants. This was done by regarding the ratio of the frequencies of revolution for the electron, and imposing a condition that they tend to 1 for large quantum numbers, since this would make frequency of radiation during transition, fit the classical results [10]. The variety of the principle is especially highlighted in relation to electron transitions in the atom.

1.2 Electron Transitions

In 1887, Otto Staude showed that if the Hamilton-Jacobi equation could be separated into a product of functions, depending on different variables for a system with two degrees of freedom[2], then the motion of the system would be multiply periodic. The motion can

[2]Later Paul Stäckel extended this to arbitrary finite degrees of freedom

then be described by a Fourier series [11]. For a central potential the relevant conditions are met, thus, regarding a simple system of an electron with one degree freedom, the coordinate can be expressed as

$$x(t) = \sum_{n=0}^{\infty} C_n \cos(n\omega t) \tag{3.1}$$

where $n\omega$ are the various periods of the motion. When the electron makes a transition from one orbit to another, the emitted radiation will have the frequency $f_n = n\omega$, where ω is called the fundamental frequency. This means that from a classical description all emission-lines of a spectrum would be evenly spaced [14].

In Bohr's model of the atom the transition between stationary states happened with the emission of radiation whose frequency was given from the Bohr-Einstein condition $f = \frac{E_n - E_m}{h}$, $n \to m$, unlike the classical description. However, as the quantum number n grows large, the spacing between the states tends to a constant value. Thus, for large n the classical prediction for the frequency of the emitted radiation corresponds to the prediction of (old) quantum theory. Furthermore, the constants C_n represents the intensities of the emitted radiation in the classical description. In the quantum description, light is quantized in photons and the intensity then corresponds to the number of emitted photons, which in turn is a measure for the probability of a given transition. Since the associated frequencies to each constant C are the emitted frequencies for large n, the square modulus of the constants correspond to the probability of the respective transition in this limit; $P_{n\to n-k} = C_k$ for large n. The correspondence principle introduced the concept of probability to the quantum theory[3] [10, chapter 3]. Lastly, the Fourier series was used by Bohr to show which transitions were allowed:

> *The possibility of the occurrence of a transition, accompanied by radiation, between two states of a multiply periodic system, of quantum numbers for example $i_1, ..., i_u$ and $j_1, ...j_u$, is conditioned by the presence of certain harmonic components in the expression given by* [referring to the Fourier series expansion of the classical motion] *The frequencies $\tau_1\omega_1 + ... + \tau_u\omega_u$ of these harmonic components are given by the following equation*
>
> $$\tau_1 = i_1 - j_1, ..., \tau_u = i_u - j_u$$
>
> *We, therefore, call these the "corresponding" harmonic components in the motion, and the substance of the above statement we designate as the "Correspondence Principle."* [4] [12, p 479]

The Harmonics in the Fourier expansion can be used to determine which transitions are allowed. For example if the Fourier expansion includes the harmonic $\cos(k\omega t)$, then transitions of the type $n \to n - k$ are allowed or, stated differently, transitions where $\Delta n = k$. Unlike the previous interpretation, this interpretation of the correspondence principle holds for small n, and could thus be judged to be in accordance with Bohr's statement that the correspondence principle is a law of quantum theory. This implies that there is more to the correspondence principle than merely reducing to classical physics in

[3] The inspiration to do this came from an article of Einstein [10, p 112], which in hindsight seems ironic, given Einstein famous distaste for chance expressed in his quote: "God does not play dice"

[4] The mathematical notation of the quote has been slightly altered to better correspond to the notation that is used here.

the limit of large quantum numbers. Indeed, Bohr himself allegedly expressed this very notion:

> *it is not the correspondence argument. The requirement that the quantum theory should go over to the classical description for low modes of frequency, is not at all a principle. It is an obvious requirement for the theory.* [16, p 690]

These different features have all been associated with the correspondence principle by Bohr himself, which has given rise to different interpretations of the correspondence principle. Furthermore, because of seemingly contradictory statements regarding the correspondence principle, it has even been claimed that it is impossible to assign a single clear-cut description of what Bohr viewed the correspondence principle to be [14]. The principle did nonetheless play a significant role in developing the old quantum theory. The principle can even been used to give justification to the general quantum conditions such as quantization of action and to motivate the use of matrices in quantum mechanics.

1.3 Motivating the Matrix

Heisenberg used the correspondence principle in his work as well, leading to the formation of matrix mechanics. In classical physics, any time-dependent quantity $O_n(t)$ can be represented by a Fourier expansion

$$O_n(t) = \sum_{j=-\infty}^{\infty} A_{n,j} \exp(2\pi i f_{n,j} t) \tag{3.2}$$

where $A_{n,j}$ is the amplitude and $f_{n,j} = j f_n$ is the frequency of the j'th term. Bohr used the correspondence principle to associate a given frequency of the Fourier expansion $f_{n,j}$ with a transition between quantum states that differed in their quantum number by j. Extending this association Heisenberg hoped to derive another quantity that could have a role in quantum realm. First Heisenberg thought the amplitude might correspond to such a quantity.

$$f_{nj} \leftrightarrow f(n, n-j) \qquad A_{nj} \leftrightarrow A(n, n-j). \tag{3.3}$$

The parenthesis following the quantities is to emphasize its description of processes between states. However, Heisenberg realized that simply replacing the terms in (3.2) by (3.3), would not hold any physical significance, since the indices have equal status. From the quantities definitions in regards to the Fourier expansion and the condition of reality, they posses the following properties

$$\begin{aligned} f_{i,-j} &= -f_{i,j} \quad & f(n-j, n) &= -f_{n,n-j} \quad & A(n-j, n) &= A^*(n, n-j) \\ A_{n,-j} &= A^*_{n,j} \quad & f_{n,j} + f_{n,j'} &= f_{n,j+j'} \quad & f(n, n-j) + f(n-j, n-j') &= f(n, n-j'). \end{aligned} \tag{3.4}$$

From these, Heisenberg was inspired to assume that a term in the Fourier series might be the quantum mechanical representative of a classical quantity [10, chapter 5]

$$O_n \leftrightarrow A(n, n-j) \exp(2\pi i f(n, n-j) t). \tag{3.5}$$

Heisenberg then asked how the representation of the quantum mechanical quantity, i.e a term in the Fourier series, squared would look like? If one found a solution to this, then one could extrapolate how quantum mechanical quantities must be multiplied.

Regarding classical physics and using the properties (3.4), it can be shown that [10, chapter 5]

$$O_n^2 = \sum_{j=-\infty}^{\infty} A_{n,j}^{(2)} \exp(2\pi i f_{i,j} t) \tag{3.6}$$

where $A_{n,j}^{(2)} = \sum_{j'=-\infty}^{\infty} A_{n,j'} A_{n,j-j'}$. The square of $A_{n,j}$ is not a square in a regular sense, hence the parenthesis around the 2, but is a square through the quantum mechanical multiplication rule, that Heisenberg was trying to deduce. By assuming his original assumption (3.5) then

$$O_n^2 \leftrightarrow A^{(2)}(n, n-j) \exp(2\pi i f(n, n-j)t) \tag{3.7}$$

How then, can the product of the quantum mechanical quantities $A^{(2)}(n, n-j)$ be extrapolated? By using (3.3) on (3.6) one arrives at the following expression for each term in (3.6) over the sum of j

$$\sum_{j'=-\infty}^{\infty} A(n, n-j')A(n, n-(j-j')) \exp\big(2\pi i f(n, n-j')t\big) \exp\big(2\pi i f(n, n-(j-j'))\big) \tag{3.8}$$

which does not agree with (3.7), because of the phases. Heisenberg's insight was that one had to replace the phases, so that the expression would agree with his assumption (3.5), and therefore (3.7). This can be achieved by replacing $\exp(2\pi i f(n, n-j')t) \exp(2\pi i f(n, n-(j-j')))$ with $\exp(2\pi i f(n, n-j')t) \exp(2\pi i f(n-j', n-j))$, which makes the expression agree with (3.7). This replacement can be used as a guide to find the multiplication rule of $A(n, n-j)$ [10, chapter 5]. Each term, representing a physical quantity by (3.5), therefore becomes

$$\begin{aligned}
&\sum_{j'=-\infty}^{\infty} A(n, n-j')A(n-j', n-j) \exp\big(2\pi i f(n, n-j')t\big) \exp\big(2\pi i f(n-j', n-j)\big) \\
&= \left(\sum_{j'=-\infty}^{\infty} A(n, n-j')A(n-j', n-j)\right) \exp\left(2\pi i f(n, n-j)\right)
\end{aligned}$$

so the quantum mechanical multiplication rule becomes

$$A^{(2)}(n, n-j) = \sum_{j'=-\infty}^{\infty} A(n, n-j')A(n-j', n-j). \tag{3.9}$$

Generalizing this product rule for two physical quantities O_n and P_n, one notices that $O_n P_n \neq P_n O_n$! The quantum mechanical product rule is thus not commutative and is actually the same product rule as that of matrices [10, chapter 5].

Though it might not be clear what Bohr's concept of the correspondence principle exactly was, its numerous interpretations have played a very significant role in the development of quantum mechanics. Its role was, however, more a tool for developing quantum mechanics, not interpreting it. Max Jammer writes about the correspondence principle:

There was rarely in the history of physics a comprehensive theory which owed so much to one principle as quantum mechanics owed to Bohr's correspondence principle. [10, p 118]

2 The Uncertainty Relation

The uncertainty principle was conceived and presented by Heisenberg in 1927, before Bohr's Como lectures and his presentation of complementarity. They came in the mist of Schrödinger's visit to Copenhagen and his following discussions with Bohr[5]. It was known that it was not possible to completely specify the values of two conjugate variables at the same time, which was implied by the fact that the operators representing the variables did not commute

$$pq - qp = -i\hbar. \tag{3.10}$$

Heisenberg asked himself when formulating the uncertainty relation, to what degree is it possible, to specify conjugate variables at the same time [10, p 325]

This led Heisenberg to his now famous relation

$$\Delta p \Delta q = \frac{\hbar}{2} \tag{3.11}$$

"*The more accurately the position is determined, the less accurately the momentum is known and conversly*" [10, p 16] was how Heisenberg expressed it. This then shows how the commutation relations of conjugate operators are to be interpreted $[q, p] = -\frac{i}{2}\Delta q \Delta p$. The uncertainty relation can be interpreted as an ontological consequence; the variables in question are not well-defined at the same time and the uncertainty principle relates to the applicability of the classical concepts the variables pertain to. The principle can also be interpreted as a epistemological consequence; the uncertainty principle sets a limit to our knowledge of the variables, they may, however, be well-defined, thereby preserving causality. The uncertainty relation can also be used to explain the statistical nature of quantum mechanics, as Heisenberg expresses:

"*We have not assumed that quantum theory, unlike classical physics, is essentially a statistical theory in the sense that from exact data only statistical conclusions can be inferred. For such an assumption is refuted for example by the well-known experiments by Geiger and Bothe. However in the strong formulation of the causal law 'If we know exactly the present, we can predict the future' it is not the conclusion but rather the premise which is false. We can not know as a matter of principle, the present in all details... it may be suggested that behind the statistical universe of perception there lies hidden a 'real' world ruled by causality. Such speculations seem to us - and this we stress with emphasis - useless and meaningless. For physics has to confine itself to the formal description of the relations among perceptions.*" [10, p 331]

The preceding may make it seem as though Heisenberg regarded the uncertainty relation as an epistemic consequence, however, this is refuted by Max Jammer he indicates that it seems more likely that Heisenberg actually regarded the uncertainty principle as ontic. However, in Heisenberg's book "Physics and Philosophy", Heisenberg coins the term

[5] These discussion are painted as extremely long and arduous in different historical literature [12, p 6]

"the Copenhagen interpretation". In the section concerning it, Heisenberg speaks of a deficiency of knowledge, which would seem as an epistemological interpretation. This will be taken as Heisenberg's stance from here on out. Furthermore, the suggestion that there may be a hidden causality in nature seems to contrast Bohr's thoughts on complementarity of space-time coordination and causality, which will be covered in the next section. Indeed the views of Bohr and Heisenberg concerning quantum mechanics are not the same, which will be explored further later.

3 Complementarity

The correspondence principle was used extensively to derive quantum theory, but held little metaphysical value, other than linking quantum mechanics and classical mechanics. In 1927 Bohr presented a new concept that contained many implications to the metaphysical nature of quantum mechanics, namely the concept of complementarity.

Bohr presented the concept in Como 1927 where he gave a lecture to an audience, including some of the most prominent physicists at the time. These lectures were some months after Heisenberg had published his paper regarding the uncertainty principle, thus giving rise to speculation that complementarity was derived from the uncertainty relations by Bohr, this is however rejected by several sources [15] [12] [10], who imply that the uncertainty principle may be seen as a consequence of the principle of complementarity. According to [12] Bohr had the inklings of complementarity in his mind, for some time, and it was while he was on holiday in Norway, incidentally the same time that Heisenberg formulated the uncertainty relations, that Bohr was able to formulate the principle. At this time there were conflicting views on how to interpret the two emergent formulations. The motive to give a clear explanation must have driven Bohr to contribute to the discussion [12].

This concept serves little technical purposes, i.e. it does not play any significant role in the application of the formalism, however, it carries a great deal of importance in giving a coherent understanding of quantum mechanics. The concept is notoriously difficult to give a rigorous and strict definition of and there have been diverging understandings of the principle, even among the so-called fathers of the Copenhagen interpretation; Heisenberg and Bohr. The basis of complementarity, that Bohr presented in his Como lecture, takes its premise in the quantum postulate[6], that specifies that a discontinuity or a limit for analysis must be attributed to every atomic process[7] [10, p 347]

"Accordingly, an independent reality in the ordinary physical sense can neither be ascribed to the phenomena nor to the agencies of observation"

This is a complete deviation from classical physics, for it states that nature is only susceptible to our analysis to a certain limit and that we cannot explore nature beyond this limit. It is argued here that it is this very notion that make most deter from the Copenhagen interpretation and seek other ontological interpretations of quantum mechanics, as argued by David Albert [48], as it is this notion that contains the epistemological character of the Copenhagen interpretation. The quantum postulate and the limit of our

[6]Physics is quanta

[7]This assertion is made by Jammer, but in Bohr's mention of the quantum postulate, during the Como lecture, it is not evident that Bohr is speaking of a limit of all analysis, only of classical concepts

inspection is symbolized by Planck's constant as it sets a limit to how small changes the action can undergo.

Bohr elaborates that the quantum postulate makes it impossible to give a causal space-time description of an event. Classical physics is marked exactly by the union of these two descriptions, but in quantum mechanics, the two description become complementary: The one description excludes the other, but both are needed to give a complete description [13].

The laws of classical physics govern physical systems, that are not subject to outside influences. If a system of interest is influenced from the outside of said system, then one can regard a larger physical system, that has no influences from outside the system, encompassing the system of interest and applying classical laws to this system. However, when performing a measurement on a quantum system, the quantum postulate implies that the system is interacting with a system described by classical concepts, not quantum mechanics, and thus an outside influence that cannot be incorporated in a larger system is realized. Causality cannot be established in a quantum system when measurements are being performed, since the system has an outside influence, i.e. the measurement. On the other hand concepts such as position, momentum and energy only have meaning when a measurement is being performed, i.e. the space-time coordination can only be realized during a measurement [10, p 352].

"On one hand, the usual definition of the state of a physical system claims the elimination of all external disturbances. But then according to the quantum postulate any possibility of observation will be excluded. On the other hand, if in order to make observation possible we permit certain interactions with suitable means of measurement, not belonging to the system, an unambiguous definition of its state is naturally no longer possible, and there can be no question of causality in the ordinary sense of the word." [13, p 114]

3.1 Wave and Particle

As an example of the use of the complementarity principle regard light. The nature of light had been firmly established in the 19th century through experiments that made light exhibit wave properties, such as interference and diffraction. Furthermore, it was given a firm theoretical base by Maxwell's equations. However, this was challenged trough the work of Einstein in 1905 concerning the behaviour of light, it was realized that the wave description of light was not able to describe all the properties of light. Thus, Einstein proposed the quantization of light, in continuation of the quantization that Planck had introduced to describe the radiation of a black-body. Einstein's quantum, i.e. the photon, has an energy E given by its frequency f, or the period of vibration T, and Planck's constant $E = hf = \frac{h}{T}$. Extending this to $p = \frac{h}{\lambda}$ one can relate the physical quantities through Planck's constant [13, p 117]

$$\overset{\text{particle}}{E}\ \underset{\text{wave}}{T} = \overset{\text{particle}}{p}\ \underset{\text{wave}}{\lambda}\,. \tag{3.12}$$

As highlighted above, these various quantities relate to the different descriptions of light. Energy and momentum are physical quantities that relate to particles and are necessary to describe phenomenon such as Compton scattering and photoelectric effect perceived at atomic scales. On the other hand, the period and wavelength of vibration relates to waves and are necessary to describe the propagation of light and phenomenons such as diffraction and interference. The particle properties make it possible to specify a space time coordination, but the wave properties pertain to a plane harmonic wave that extends over all space, and thus makes it impossible to specify a space time coordination. To try and make it possible to give a space-time coordination of the wave, one must limit the extent of plane harmonic wave through the superposition principle. The interference pattern, that emerges from a group of harmonic plane waves, limits the extent of the waves and a space time coordination is no longer impossible[8]. This makes it possible to associate a velocity to the wave by the group velocity [13, p 6].

Regard a plane wave in one dimension, which is described by the angular frequency and wave number respectively given by $\omega = \frac{2\pi}{T}$ and $k = \frac{2\pi}{\lambda}$

$$A\cos\left(\omega t - kx + \delta\right))$$

where A is the amplitude and δ is the phase. The phase velocity is then given by $v_{phase} = \frac{\omega}{k}$ while the group velocity is given by $v_{group} = \frac{d\omega}{dk}$. Relativity can now be used to specify these quantities since

$$\frac{E}{p} = \frac{c^2}{v} \qquad\qquad \frac{dE}{dp} = v \tag{3.13}$$

From (3.12) it is seen that $\frac{E}{p} = \frac{\lambda}{T} = \frac{\omega}{k}$ so the phase velocity of the wave is $\frac{c^2}{v}$ and the velocity is v. However, by relating a velocity to the wave, the phase velocity has become ill-defined, since it is larger than the speed of light. By attributing the wave a space-time coordination, the particle properties momentum and energy have become ill-defined. One cannot unite the particle and wave properties of light at the same time. When using one description it excludes the other, but both are needed to give a full description of light. These thoughts can also be extended to matter waves, such as the electron. The electron is usually associated with a particle, but exhibits wave properties, for instance in the double slit experiment [13]

3.2 Kinematic and Dynamic

The quantum postulate implies that there is a limit to our analysis. This could be interpreted as a limit to our knowledge of physical quantities, only nature knows the values of these quantities. However, this was not the intended interpretation of Bohr. In Bohr's mind the classical concepts that we use to describe nature are not meaningful at the atomic level. The concepts we have developed to describe and understand nature, stems from our experience at our scale. When we apply these concepts to atomic scales we extrapolate the concepts to apply at this scale, and it is this extrapolation that is rejected. It is not a complete rejection of the concepts however, only a restriction. The application of these concepts is only possible when measurements are being performed and not all concepts can be applied at the same time. Position can be applied to atomic scales, but not at the same time as momentum for example. The mutually exclusive concepts were labelled the kinematic and dynamic properties by Bohr. Specifying the values of the kinematic properties excludes the specification of the values of the dynamic properties, but both are needed to give a complete description of quantum phenomenon, just not at the same time.

It was important for Bohr to still maintain the classical concepts, since it is trough these concepts that we have come to understand nature. Any understanding of nature

[8]Its not straightforward either though. The extent of the wave has been limited, but there are still infinite groups to associate with a space-time coordination

cannot occur without these concepts according to Bohr. Furthermore, Bohr talked of renunciation space-time coordinates and causality at the same time, since these concepts are not well-defined. The language implies that Bohr had more of an ontic approach to quantum mechanics than Heisenberg, which has also been argued by others [43] . This is a stance that is taken to represent Bohr.

4 Collapse of the Wave Function

According to quantum mechanics systems are in a superposition of several states, although we only measure definite states; when we measure the spin of a particle with an apparatus, the apparatus tells us that the particle either has spin up or down, not both. This is the aforementioned measurement problem, which each interpretation handles differently and is often portrayed to be the biggest problem of the Copenhagen interpretation. The Copenhagen interpretation does give an explanation to solve the measurement problem though. While most of the other elements in the Copenhagen interpretation stems from Bohr's and Heisenberg's thoughts concerning quanutm mechanics, the proposal to give a formal solution to the measurement problem came from John Von Neumann a German mathematician. Indeed Von Neumann was the first to give a formal consistent description of quantum mechanics in "Mathematical foundations of Quantum Mechanics". So far the evolution of the wave function has been completely determined by the wave equation, however Heisenberg had proposed that the wave function reduces upon measurement and thus classical concepts, such as position, only come to existence upon measurement.

"*I believe the genesis of the classical "orbit" can be precisely formulated thus: the "orbit" only comes into being by our observing it*" [17]

Furthermore, Heisenberg had postulated that when one performs a measurement, one reduces the wave function.

Thus, each position determination reduces the wave packet again to its original dimension... [17]

However, Heisenberg never touched upon the mechanism that instigated the reduction of the wave function. This reduction of the wave function of course seemed very mysterious, but it gave a solution to the measurement problem.

Enter Von Neumann who postulated that the wave function evolves through two distinct processes. One is through the Schrödinger equation, so when a system of interest S is measured by an apparatus A to measure the quantity Q, the two systems become entangled[9]. Say the apparatus is in prepared state φ before measurement, the first process causes the complete system to be in a superposition of the products between each eigenstate ϕ_i of S with respect to the observable Q and φ

$$\psi_{S+A} = \varphi \sum_i c_i \phi_i \tag{3.14}$$

where c_i is the coefficient for the i'th term. Such states were earlier shown to be written as

[9]This entanglement will be explored further in the section concerning the many worlds interpretation

$$\psi_{S+A} = \sum_i c_i \phi_i \varphi_i \tag{3.15}$$

where φ_i corresponds to a pointer state that measures the the eigenvalue q_i of ϕ_i. After this process has taken place, the wave function evolves through a process not described by the Schrödinger equation, this is the second process postulated by Von Neumann. This second process is non-linear and causes the superposition to collapse to a certain eigenstate. This collapse is an indeterministic process and it is impossible to predict which state the superposition will collapse to. However, it is possible to asses the probability of the superposition collapsing to a certain state. This is done by the Born rule, which shows that the probability of q_i being registered by the apparatus, i.e. the wave function collapsing to the state $\phi_i \varphi_i$, is given by the square amplitude of the coefficient in the superposition $|c_i|^2$ [18].

Quantum mechanics is thus inherently an indeterministic theory according to the Copenhagen interpretation, because of the non-linear process postulated by Von Neumann explaining the fact that we do not measure superposition. This process though is unaccounted for in the Copenhagen interpretation, but collapse interpretations with a formal description of the collapse process do exist. Though it is not possible to determine the exact outcome of a measurement, the Born rule makes it possible to describe the probabilities of certain outcomes, however, it also obscures the nature of the wave function. Is it an ontic quantity or an epistemic?

5 The Born Rule and An Epistemic Interpretation

The Born Rule was discovered by Max Born. Up till then very different views where held on the nature of the wave function. Schrödinger regarded the wave function to be ontic, a physical real quantity, and regarded the physical world only to be made of waves [11, p 27]. This interpretation, however, had several problems, one was that it predicted the wrong spacing in spectres. Max Born's proposal was that $|\psi|^2$ should be interpreted as the probability, and it was this probability that adhered to causality, not the properties of the systems. Max Born said of his interpretation:

"*The motion of particles conforms to the laws of probability, but the probability itself is propagated in accordance with the law of causality.*" [11, p 40]

According to Born's interpretation, the wave function does not represent a physical real quantity, but is epistemic in nature and pertains to our knowledge of the system. From this assertion the process governing collapse is evident, as when we measure a system our knowledge changes from "what could be" to "what is", representing a reduction in the wave function. However, Born's interpretation could not account for the observations made in the double slit experiment, since it says that probability is a superposition of the two probabilities emerging from each slit if the other was closed. To explain the double slit experiment, one must account for the interference of each wave emerging from each slit, but this implies that the wave function is physically real! While Heisenberg took to the interpretation and regarded the wave function as a purely epistemic quantity, since the classical concepts no longer applied at the quantum level. Bohr shared the view that the classical concept did not apply at the atomic scale, but his view on the nature of the quantum state are still debated, but the Copenhagen interpretation is widely regarded as an epistemological interpretation, since it states that nature can only be investigated to a certain degree [43].

As previously mentioned the Copenhagen interpretation is not a homogeneous collection of thoughts. The term came to be from people opposing the interpretation or from Heisenberg's representation of the views of the Copenhagen school. However, this representation gives the impression that there was a consensus concerning various concepts, which subsequently has been shown not to be true. The Copenhagen interpretation has been used as a term without it having been given any form of definition. This vagueness has even been argued to be one of its appeals, since it thus can incorporate so many different views [15]. To this day it still reigns as the most favoured interpretation [2], however, more and more alternatives to the interpretation are emerging. Interpretations with more strict definitions.

Chapter 4

Problems of the Standard Quantum Mechanics

The Copenhagen interpretation was the first established interpretation of quantum mechanics, it completed the theory. From now on in this thesis the theory interpreted through the Copenhagen interpretation, will be referred to as standard quantum mechanics. This standard quantum mechanics was accepted at the time, but it still had its opponents, e.g. in Einstein. This lead to Einstein trying to refute quantum mechanics through experiments and debates with Bohr. However, for each objection Einstein raised Bohr seemed to have an answer, therefore Bohr was viewed to be "the winner" of these Bohr-Einstein debates [15]. Einstein had one objection, though, that left a considerable imprint and quantum mechanics.

1 The EPR Paradox

Albert Einstein, Boris Podolsky and Nathan Rosen contemplated what is today known as the EPR-paradox[1]. It was meant to show that quantum mechanics is incomplete. The paper, concerning this argument, first defines what a complete theory is, or rather necessary requirements of a physical theory by stating,

Every element of the physical reality must have a counterpart in the physical theory [4]

Here the term *physical reality* is somewhat vague and ill-defined, however the paper tries to clarify this point by asserting that

If, without in any way disturbing a system, we can predict with certainty (i.e., with probability equal to unity) the value of a physical quantity, then there exist an element of physical reality corresponding to this quantity.[2] [4]

The paper then delves into the uncertainty principle and that not all physical quantities can be attributed to a system at the same time; the ascription of some physical quantities will exclude the ascription of others. This implies that either quantum mechanics is incomplete or two mutually exclusive quantities cannot have a simultaneous physical reality, from the prescriptions given above [4].

[1] From the surnames of the authors

[2] This notion seems very contrasting to the thoughts of Bohr, which will be explored later.

However, if two systems interact and afterwards become independent of one another, the total system will be in superposition of the product of the eigenvectors spanning the two Hilbert spaces. Specifically suppose that two systems interact in the time t, where $0 \leq t \leq T$. The two systems have the eigenstates φ_i and ϕ_i of the observable A. After the time T the two systems are not interacting any more, and the wave function for the total system can be expressed as

$$\Psi^T = \sum_{i=1}^{\infty} C_i \varphi_i \phi_i. \tag{4.1}$$

When a measurement of observable A is performed on one system, it will return an eigenvalue a_k pertaining to the eigenstate φ_k. The measurement makes the wave function reduce[3] to a single term, and thus the other system ends up in a certain eigenstate as well without a measurement being performed on the system, i.e.

$$\psi^T = \sum_{i=1}^{\infty} \varphi_i \phi_i \underset{\text{measurement}}{\rightarrow} \psi^T = \varphi_k \phi_k$$

However, if instead one was interested in the observable B, one would decompose the state of the total system in eigenstates of this observable, say ξ_i and η_i, so (4.2) would become

$$\psi^T = \sum_{i=1}^{\infty} \xi_i \eta_i, \tag{4.2}$$

and the measurement of B on one system would again reduce the wave function of the total system to one term

$$\psi^T = \sum_{i=1}^{\infty} \xi_i \eta_i \underset{\text{measurement}}{\rightarrow} \psi^T = \xi_k \eta_k,$$

Thus, it is seen that one can assign two distinct wave functions to system 2, without it interacting with anything. If the two observables A and B do not commute, they represent mutually exclusive quantities, but both these quantities are given a well-defined values in system 2, without in any way disturbing it. Thus, two mutually exclusive quantities are given reality simultaneously, thus contradicitng the earlier statement and one must conclude that quantum mechanics is incomplete. Furthermore Einstein, Podolsky and Rosen claim that there must be some hidden variables that specify the system further, in order to give a coherent theory [4]. Such theories have since been constructed, as will be displayed later. It is safe to say though that they are of a very different nature than the one Einstein, Podolsky and Rosen had in mind.

The EPR paper places a great deal of emphasis on the definition of physical reality and how a physical theory should relate to it, however, this was not of great importance to Einstein as can be seen in his work immediately following the publishing of the EPR-paper. Einstein was indeed more concerned with the conflict of locality embedded in quantum mechanics through entangled systems [47].

[3]The concept of reduction or collapse has not been introduced yet, as it belongs to the Copenhagen interpretation.

1.1 Bell's Theorem

The EPR paradox is the starting point for John Bell[4] in deriving an inequality that shows that the results of quantum mechanics are not compatible with hidden variables in a local theory. Bell takes a particular scheme of the EPR-argument, one conceived by David Bohm, who will play a central role later. This scheme regards the decay of a neutral pion to an electron and positron. From conservation of momentum the two particles move in opposite directions and from conservation of angular momentum the two particles must have opposite spin and be in the singlet state. After the particles have moved away from each other, without interacting with anything, measurement of the particles spins are performed at point A and point B. These points are assumed to be so far from each other that they cannot interact or influence one another in any way. Locality is thus assumed. The measurement at A concerns the spin of the particle in the direction of a unit vector $\mathbf{a}$, while the measurement at B concerns the spin of the particle in the direction of a unit vector $\mathbf{b}$. Each measurement will yield either 1 or -1.

$$A(\mathbf{a}) = \pm 1 \qquad B(\mathbf{b}) = \pm 1 \tag{4.3}$$

Where A and B now represents functions that return the value 1 if the spin has a component along respectively $\mathbf{a}$ or $\mathbf{b}$, or it returns the value -1 if the spin has component opposite the vectors [5]. Since the two points do not interact with one another, the measurement at B cannot depend on $\mathbf{a}$ and vice versa. If hidden variables exist, these functions must also depend on these hidden variables, then

$$A(\mathbf{a}, \lambda) = \pm 1 \qquad B(\mathbf{b}, \lambda) = \pm 1 \tag{4.4}$$

where λ denotes the hidden variables. No assumptions of the nature of the hidden variables are being made, so λ could describe one variable or a multitude of variables, be either continuous or discrete. For the sake of concreteness, λ is taken to be continuous, but the analysis can easily be extended to case where λ is discrete. The expectation value of the product of these function $P(\mathbf{a}, \mathbf{b})$, i.e. the measured results, must be taken over the hidden variables[5]

$$P(\mathbf{a}, \mathbf{b}) = \int \rho(\lambda) A(\mathbf{a}, \lambda) B(\mathbf{b}, \lambda) d\lambda \tag{4.5}$$

where $\rho(\lambda)$ denotes the normalized probability distribution of λ, i.e.

$$\int \rho(\lambda) d\lambda = 1. \tag{4.6}$$

(4.5) should equal the regular quantum mechanical result $-\mathbf{a} \cdot \mathbf{b}$, if hidden variables are to explain the well-corroborated results of quantum mechanics. The expectation value of the products in quantum mechanics, would thus solely be

$$< A(\mathbf{a}) B(\mathbf{b}) >= -\mathbf{a} \cdot \mathbf{b} = -\cos\theta, \tag{4.7}$$

where the dot denotes the scalar products between the vectors and θ is the angle between $\mathbf{a}$ and $\mathbf{b}$. Returning to the hidden variables, notice that because of the normalization

[4] His paper was titled "On the Einstein Podolsky Rosen Paradox"

[5] For the discrete case, the integral is replaced by a sum.

(4.5) can never be less than -1. It can only be -1 if $\mathbf{a} = \mathbf{b}$ since the components of the spin are opposite for the two particles. The functions $A(\mathbf{a}, \lambda)$ and $B(\mathbf{b}, \lambda)$ must satisfy

$$A(\mathbf{a}, \lambda) = -B(\mathbf{b}, \lambda). \tag{4.8}$$

for (4.5) to equal -1. The condition (4.8) is taken as a general rule, necessary to give the right quantum mechanical predictions. With this condition (4.5) can be rewritten

$$P(\mathbf{a}, \mathbf{b}) = -\int \rho(\lambda) A(\mathbf{a}.\lambda) A(\mathbf{b}, \lambda) d\lambda. \tag{4.9}$$

Introducing another unit vector $\mathbf{c}$ it follows that

$$\begin{aligned} P(\mathbf{a}, \mathbf{b}) - P(\mathbf{a}, \mathbf{c}) &= -\int \rho(\lambda) A(\mathbf{a}, \lambda) A(\mathbf{b}, \lambda) - \rho(\lambda) A(\mathbf{a}, \lambda) A(\mathbf{c}, \lambda) d\lambda \\ &= \int \rho(\lambda) A(\mathbf{a}, \lambda) A(\mathbf{b}, \lambda) \Big(A(\mathbf{b}, \lambda) A(\mathbf{c}, \lambda) - 1 \Big) d\lambda. \end{aligned}$$

Using (4.4)

$$\begin{aligned} &|P(\mathbf{a}, \mathbf{b}) - P(\mathbf{a}, \mathbf{c})| \leq \int \rho(\lambda) \Big(1 - A(\mathbf{b}, \lambda) A(\mathbf{c}, \lambda) \Big) d\lambda \\ &\Updownarrow \\ &|P(\mathbf{a}, \mathbf{b}) - P(\mathbf{a}, \mathbf{c})| \leq 1 + P(\mathbf{b}, \mathbf{c}) \end{aligned} \tag{4.10}$$

where (4.10) is Bell's famous inequality. This inequality is in general not consistent with the quantum mechanical prediction (4.7) [5]. As an example, regard the case where $\mathbf{a}$ and $\mathbf{b}$ are orthogonal, so that $P(\mathbf{a}, \mathbf{b}) = \mathbf{a} \cdot \mathbf{b} = 0$, and the vector $\mathbf{c}$ lies such that its angle to $\mathbf{a}$ is equal to its angle to $\mathbf{b}$, so that $P(\mathbf{a}, \mathbf{c}) = P(\mathbf{b}, \mathbf{c})$. Bell's inequality (4.10) then becomes

$$|P(\mathbf{b}, \mathbf{c})| \leq 1 + P(\mathbf{b}, \mathbf{c}) \tag{4.11}$$

which cannot be true for $P(\mathbf{b}, \mathbf{c}) < -\frac{1}{2}$, that is the angle between the vectors $\mathbf{b}$ and $\mathbf{c}$, which is also the angle between $\mathbf{a}$ and $\mathbf{c}$, being smaller than $60°$. Therefore the results of quantum mechanics are not compatible with a local hidden variables theory. Experiments have been performed to test Bell's inequality and indeed violations of it are observed [5].

Bell's inequality have far reaching consequences, not only is it not possible to give a hidden variables account of the results of quantum mechanics, but one cannot explain away the nonlocality described in the EPR-paradox. It would seem then, that there is some notion of nonlocality about nature, a notion that any interpretation must try to explain.

Chapter 5

The Many Worlds Interpretation of Quantum Mechanics

The many worlds interpretation of quantum mechanics is an interpretation that rejects the collapse postulate and treats the role of the observer as a physical system, not as an external element. The rejection of the collapse postulate means that, when a measurement is performed on a system in a generalized state, i.e. in a superposition, the observer will only observe one element of a superposition. The interpretation of the outcomes that we do not observe, i.e. the other elements in the superposition, varies, as there are different versions of the many worlds interpretation. The most popular version is one where each element corresponds to a different world, hence the name many worlds. When an observer performs a measurement, it causes different worlds to appear in each of which a different outcome of the measurement has been observed. The measurement an observer finds is the outcome that corresponds to his particular world.

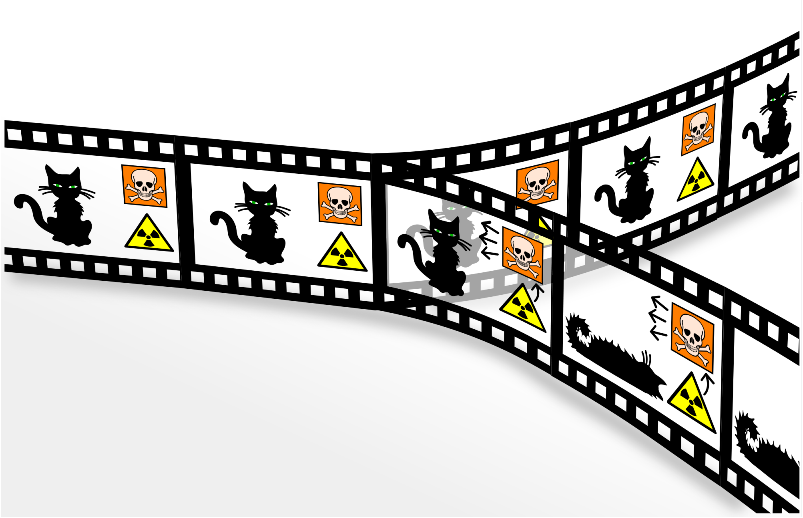

Figure 1: Illustration describing the splitting of worlds

The many worlds interpretation has evolved over time, with particular Bryce DeWitt reformulating and popularizing the theory. However, the person who first proposed the many worlds interpretation was Hugh Everett, who dubbed the formulation "Pure Wave

Mechanics", which he outlined in his dissertation from Princeton University.

The following section will provide a brief overview of Hugh Everett's original thoughts on an alternative interpretation to the Copenhagen interpretation. These thoughts form a common base, which all many worlds interpretations stem from. The section will also attempt to describe the distinctions between Everett's version and more modern versions, particularly DeWitt's version. Finally it will also describe the more troubling aspects of the many worlds interpretation, e.g. the problem of probability, and other popular objections to the interpretation.

1 Everett's Pure Wave Mechanics

1.1 The Measurement Problem and Composite Systems

There are several problems with the Copenhagen interpretation of quantum mechanics, when the theory is regarded as ontological. One problem is the role of the observer during a measurement[1]. The measurement, or rather the observer making the measurement, is according to the Copenhagen interpretation, the one who makes the system "decide" which state it is in, by instigating a collapse in the wave function. Extending this to the macroscopic world can lead to ludicrous phenomena, e.g Schrödinger's cat. This is the so-called measurement problem of quantum mechanics. The role of the observer also means that every outcome or every event needs an observer to happen. When we observe a system, we are giving this system a definite state, but what about the system we are a part of, who is giving our system a definite state? Furthermore, if there is an observer on our system, who is giving our observer's system a definite state? Any observer must be part of a physical system. Thus, the assertion that a system needs an observer to be in a definite state creates and endless set of Matryoshka dolls consisting of an observer and a system. This is also known as *Neumanns catastrophe of infinite regression* [22].

If the situation is regarded through the formalism of quantum theory, one has to look at the wavefunction of a composite system. Suppose an observer B was performing measurements on a system S, while another observer A was performing measurements on the system comprising of $B+S$. The wavefunction of a system describes all physical aspects of the system, and it can change in two ways in standard quantum mechanics. Continuous change described by the wave equation, when no measurements are performed on the system, or 2) a discontinuous change caused by an observer performing a measurement on the system, i.e. a collapse of the wavefunction. So when observer A is not performing measurements on system $B+S$, the wavefunction ψ^{B+S} of system $B+S$ should evolve continuously prescribed by the wave equation. However when observer B performs a measurement on system S, he will instigate a collapse of the wavefunction ψ^{S}, i.e. a discontinuous change in ψ^{S}. The discontinuous change in ψ^{S} must cause a discontinuous change in ψ^{B+S}. This creates an inconsistency, because ψ^{B+S} must evolve continuously while observer A is not performing measurement on system $B+S$, but if observer B performs a measurement on system S it will cause a discontinuous change in ψ^{S} and thereby in ψ^{B+S}. This contradiction is the starting point for Hugh Everett when outlining his theory of the universal wave function in his long thesis[2].

[1] There is also the question of how one defines an observer and a measurement?

[2] Hugh Everett first wrote a longer version of his thesis entitled "Quantum Mechanics by the Method of the Universal Wave Function", which afterwards became "On the Foundations of Quantum Mechanics" in a significantly shorter version [20]

1.2 Relative state

Everett began by analysing a composite system with the formalism of quantum mechanics. Consider two subsystems S_1 and S_2 that comprise a system S. Because of the linearity of quantum mechanics[3] the Hilbert space of S is then a tensor product of the Hilbert spaces for S_1 and S_2

$$\mathcal{H}_S = \mathcal{H}_{S_1} \otimes \mathcal{H}_{S_2} \tag{5.1}$$

which must imply that if $\{\phi_i\}$ is a complete orthonormal set describing S_1 and $\{\varphi_j\}$ is a complete orthonormal set describing S_2 then the state describing S must be a superposition of the outerproducts of these sets

$$\psi^S = \sum_{i,j} a_{ij}\phi_i\varphi_j \quad . \tag{5.2}$$

where the a_{ij} are coefficients determined by the nature of the specific systems S_1 and S_2, and their orthonormal bases [20]. Excluding the case where all except one of the α_{ij} are zero, then the systems S_1 and S_2 have no definitive state; they are entangled[4].

Everett's idea, however, was that for any choice of state in one subsystem, say state ϕ_k for S_1, we can uniquely assign a defintive state in S_2 relative to the state ϕ_k.

$$\psi^{S_2}(\text{rel } \phi_k|S_1) = N_k \sum_j a_{kj}\varphi_j \tag{5.3}$$

Where N_k is a normalization constant. This relative state is determined uniquely by the state ϕ_k and is independent of the choice for the orthonormal complement $\{\phi_i\}$ $i \neq k$.

A relative state as (5.3) can be constructed for every state $\{\phi_i\}$ and the relative state of S_1 can as well be constructed for each state $\{\varphi_j\}$ of S_2.

This means that the composite system S consisting of the two subsystems S_1 and S_2 can be viewed as being in a superposition of the relative states.

$$\psi^S = \sum_i \frac{1}{N_i}\phi_i\psi^{S_2}(\text{rel } \phi_i|S_1) \tag{5.4}$$

$$= \sum_j \frac{1}{N'_j}\varphi_j\psi^{S_1}(\text{rel } \varphi_j|S_2) \tag{5.5}$$

The system S is in (5.4) described as a superposition of the relative states of S_2 for each $\{\phi_i\}$, while it is described as a superposition of the relative states of S_1 for each $\{\varphi_j\}$ in (5.5). This representation of the composite system S is important as it highlights the entangled nature of the subsystems, and how definitive states of the subsystems do not exist in quantum mechanics [20]. It is also the foundation of all variations of the many worlds interpretation. Everett remarks in his thesis:

There does not in general exist anything like a single state for one subsystem of a composite system. Subsystems do not possess states that are independent of the states of the remainder of the system, so that the subsystem states are generally correlated with one another. One can arbitrarily choose a state for one subsystem, and be led to the relative

[3] $\mathbf{A}\Psi = \mathbf{A}\psi_1 + \mathbf{A}\psi_2 + ... + \mathbf{A}\psi_N$

[4] The system S though has the definitive state 5.2

state for the remainder. Thus we are faced with a fundamental "relativity of states", which is implied by the formalism of composite systems. It is meaningless to ask the absolute state of a subsystem - one can only ask the state relative to a given state of the remainder of the subsystem. [21]

1.3 Consistency

Everett expresses his motivation for formulating pure wave mechanics was to create a framework of quantum mechanics without any inconsistencies. Thus, to solve the measurement problem, he modelled observers as physical systems unlike conventional quantum mechanics where they are treated as external elements. Performing a measurement, then, corresponds to letting the observer-system interact with the system of interest. The measurement process becomes a question of analysing a composite system consisting of the observer and the system of interest. Everett gives a definition of a good observer, or rather a good observer state, as one whose state changes when the observer has made a measurement[5]. Say an observer O observes an event A, then we will write

$$\psi^O \rightarrow \psi'^O_{[A]} \quad . \tag{5.6}$$

If observer O observes an unspecified number of events in the sequence A, B...C we will write

$$\psi^O \rightarrow \psi'^O_{[A,B,\cdots,C]} \quad . \tag{5.7}$$

Since every measurement is an interaction between the observer and the physical system of interest, one should define what constitutes a good observation, i.e how the states of the system and observer behave. Regard an observer O with ψ^O, who performs a measurement of a quantity A, with eigenfunctions $\{\phi_i\}$, on a physical system S. The two systems then interact in a specified amount of time which transforms the state of the total system $O+S$

$$\psi^{O+S} = \phi_i\psi^O \rightarrow \psi'^{O+S} = \phi_i\psi^O_{[\alpha_i]} \tag{5.8}$$

where α_i characterizes ϕ_i.[6] A good observation is then a interaction that leaves the system state unchanged, if it is an eigenstate of A, and the observer state being made aware of the specific eigenfunction[7].

Suppose a system is not in an eigenstate of an observable A. The general state will then be in superposition of the eigenstates of A, i.e. $\psi^S = \sum_i a_i\phi_i$. When we perform measurements, we do not observe superpositions. However when the observer state is moved under the summation sign, so each term consist of an eigenstate and an observer state, then each term becomes $\phi_i\psi^O \rightarrow \phi_i\psi^O_{[\alpha_i]}$. Thus when an observer O performs a measurement on system S, the total state of $O+S$ will change to

$$\psi'^{O+S} = \sum_i \phi_i\psi^O_{[\alpha_i]} \quad . \tag{5.9}$$

[5]For further details on the nature of the observer see [20, chapter 5]

[6]This could be a recording of the eigenvalue to ϕ_i

[7]In the following every observation considered will be assumed as well as every observer will be assumed good

In the previous section it was shown that the formalism of quantum mechanics describes composite systems as a superposition of eigenstates of one system and their relative states, so since the composite system of an observer and a system S can be written as in (5.9), the wavefuntction of the observer having registered the eigenfunction, must correspond to the relative state of the observer, i.e. $\psi^O_{\{\alpha_i\}} = \psi^O(\text{rel }\phi_i|S)$. Note that this is not an additional structure added to the formulation, but automatically comes out from the definitions of the previous section and the formalism of quantum mechanics.

If there are multiple system $S_1, S_2, ..., S_N$ which are not interacting and an observer O, then the state of the total system will be given by $\psi^{S_1+S_2+...+S_N+O} = \psi^{S_1}\psi^{S_2}\cdots\psi^{S_N}\psi^O$. If observer O then performs a measurement of observable A with eigenfunctions $\{\phi_i\}$ on system S_1, then the total system state transforms to

$$\psi'^{S_1+S_2+...+S_N+O} = \sum_i a_i\phi_i\psi^{S_2}\cdots\psi^{S_N}\psi^O_{[\alpha_i]} \quad . \tag{5.10}$$

It is seen that when a measurement is performed, the total wave function branches[8], as to incorporate every eigenfunction of the system, and every observer observing that particular eigenfunction.

If the observer then performs another observation of observable B with eigenstates $\{\varphi_j\}$ on the system S_2, the total system state transforms again

$$\psi''^{S_1+S_2+...+S_N+O} = \sum_{ij} a_ib_j\phi_i\varphi_j\psi^{S_3}\cdots\psi^{S_N}\psi^O_{[\alpha_i,\beta_j]} \quad . \tag{5.11}$$

Each element of the total wave function branches again, so every branch of the eigenfunction ϕ_i, branches to incorporate all eigenfunctions $\{\varphi_i\}$ and an observer having observed the particular eigenfunction, after having observed ϕ_i.

Furthermore, if the observer performs the first observation of observable A on system S_1 again, then because the observation of a system in an eigenstate leaves the state of the system unchanged (5.8), the total system state will be described by

$$\psi''^{S_1+S_2+...+S_N+O} = \sum_{ij} a_ib_j\phi_i\varphi_j\psi^{S_3}\cdots\psi^{S_N}\psi^O_{[\alpha_i,\beta_j,\alpha_i]} \quad . \tag{5.12}$$

Thus, the second measurement on the same system only changes the observer state, so the observer observes the same as in the first measurement.

Regard the case where the composite system consists of N identical systems, i.e. $\psi^{S_1} = \psi^{S_2} = ... = \psi^{S_N}$, and an observer O. If the observer performs a measurement of observable A with eigenfunctions $\{\phi_i\}$, on one system at a time up to system r where $r \leq N$, then the total wavefunction becomes

$$\psi'^{S_1+S_2+...+S_N} = \sum_{ij\cdots k} a_ia_j\cdots a_k\phi_i\phi_j\cdots\phi_k\psi^{S_{r+1}}\cdots\psi^{S_N}\psi^O_{[\alpha_i,\alpha_j,\cdots,\alpha_k]} \tag{5.13}$$

If the observer now performs a measurement on system S_1, then the observer will see the same results, because of the definition of a good observer (5.8). The wavefunction of the total system then becomes

[8] This happens to avoid an observation of a superposition.

$$\psi'^{S_1+S_2+\ldots+S_N} = \sum_{ij\cdots k} a_i a_j \cdots a_k \phi_i \phi_j \cdots \phi_k \psi^{S_{r+1}} \cdots \psi^{S_N} \psi^O_{[\alpha_i,\alpha_j,\cdots,\alpha_k,\alpha_i]} \tag{5.14}$$

The state $\psi^O_{[\alpha_i,\alpha_j,\cdots,\alpha_k,\alpha_i]}$ corresponds to an observer getting different measurements from identical systems, but getting the same measurement when performing the same measurement on an already measured system. This is exactly what we observe when performing measurements on identical quantum systems, i.e. the seemingly random nature of our measurements as well as the collapse of the wavefunction can be explained from pure wave mechanics [20].

2 Metaphysical interpretations

2.1 The Objective of Physical Theory

In the Copenhagen interpretation the observer of a particular system is perceived as an external element to the system, but Everett treats the system and observer as entangled systems during an observation. As previously stated these states, observer and system, are not in definite states but there exist relative states of the observer system to a particular system eigenstate. This means that every possible outcome of an experiment is represented in the superposition (5.9) by each term. The theory at its foundation is regarding the wave function of the total system consisting of the observer and the physical system which has measurements performed on it. In the extreme this can be extrapolated to encompas the wave function for the whole Universe, which was the reason that Everett named his original thesis "The Theory of The Universal Wavefunction".

The theory Everett outlined has the power to predict all the outcomes that we observe, where our observation corresponds to one of the relative states. Pure wave mechanics assumes that the wavefunction only evolves continuously through the wave-equation, and abandons the discontinuous change in the wavefunction instigated by observation according to the Copenhagen interpretation. Questions then arise concerning the relative states that we do not observe; what do they represent? How are they to be interpreted? This is where the most significant variation of the many worlds interpretations occur. Everett never mentions, in any of his work, the word "worlds". The notion of worlds is most often credited to DeWitt in an article he wrote reformulating pure wave mechanics and adding the metaphysical interpretation of the relative states that we do not observe as other worlds.

DeWitt was a central person in popularizing the many worlds interpretation, however when he first read Everett's paper, he was sceptical

I do agree that the scheme which Everett sets up is beautifully consistent; that any single one of the [relative memory states of an observer] ... gives an excellent representation of a typical memory configuration, with no causal or logical contradictions, and with "built-in" statistical features. The whole state vector ... , however, is simply too rich in content, by vast orders of magnitude, to serve as a representation of the physical world. It contains all possible branches in it at the same time. In the real physical world we must be content with *just one branch. Everett's world and the real physical world are therefore not isomorphic.* [23, p 246]

Everett wrote a response to this criticism:

First, I must say a few words to clarify my conception of the nature and purpose of physical theories in general. To me, any physical theory is a logical construct (model), consisting of symbols and rules for their manipulation, some of whose elements are associated with elements of the perceived world. If this association is an isomorphism (or at least a homomorphism) we can speak of the theory as correct, or as faithful. The fundamental requirements of any theory are logical consistency and correctness in this sense. [23, p 253]

Everett's thoughts behind what a faithful physical theory ought to do hints at how he viewed pure wave mechanics: For the theory of pure wave mechanics to be faithful there should be a homomorphism, not necessarily an isomorphism, to our physical world. All structures and systems in our physical world are represented in the theory of pure wave mechanics, however, not all structures in pure wave mechanics are represented in our world. Everett even hinted at this perception, with the remark

"*The word homomorphism would be technically more correct, since there may not be a one-one correspondence between the model and the external world* [21, p 133]".

2.2 The Notion of Worlds

Upon regarding DeWitt's reformulation of pure wave mechanics[9], one could be inclined to think that Bryce DeWitt thought a physical theory ought to be an isomorphism. He added a metaphysical interpretation to the theory, so that the relative states which are not observed, still hold a physical meaning: They correspond to parallel worlds, where the measurement has yielded other results.

This Universe is constantly splitting into a stupendous number of branches, all resulting from the measurementlike interactions between its myriad of components [22]

In DeWitts view, every time a measurement is performed on a physical system, the world splits into multiple worlds, so that each possible measurement has a corresponding world. The fact that this happens with every measurement means that the number of worlds is increasing at an extremely large rate. DeWitt's description of the splitting of universes entails that our Universe splits even when measurements are performed in another galaxy [22].

In his paper "Quantum Mechanics and reality" De Witt presents this interpretation as the EWG (Everett, Wheeler & Graham) metatheorem. However, the presentation of the theorem as a joint-agreed theorem between the three is a misrepresentation. A personal copy of DeWitt's paper was sent to Everett, in which Everett had written the word "bullshit" next to a passage where presenting Graham's clarification on Everett's views [23].

[9]His reformulation is what the majority of physicist associate with the many worlds interpretation today

2.3 The Notion of Minds

Everett never mentions worlds in his papers concerning pure wave mechanics. Everett did, however, mention branching of the wave function, and more specifically branching of the observer state system.

We thus arrive at the following picture: Throughout all of a sequence of observation processes there is only one physical system representing the observer, yet there is no single unique state of the observer (which follows from the representations of interacting systems). Nevertheless, there is a representation in terms of a superpostion, each element of which contains a definite observer state and a corresponding system state. Thus, with each succeeding observation (or interaction), the observer state "branches" into a number of different states. Each branch represents a different outcome of the measurement and the corresponding eigenstate for the object-system state. All branches exist simultaneously in the superposition after any given sequence of observations. [20]

Everett expresses that it is the observer state that branches, not the worlds. David Albert and Barry Loewer extended this notion to formulate a many minds interpretation, which states that each observer has an infinite set of minds, with a mind corresponding to a mental state with certain beliefs, memories, intentions etc.. An observer is, thus, in a superposition of different minds, corresponding to different observed properties. The minds then supervenes their properties on the physical state. Accepting this notion does away the splitting process that is somewhat ambiguous [25].

2.4 Decoherence

Modern versions of the many worlds interpretation are based on decoherence. Taking the same approach as previously, by modelling the observer as a physical system, one can model the environment as a physical system as well. Let $S + E$ denote the total system, consisting of the environment E and a physical system of interest S. When a measurement is performed, the environment and the system inevitably interact. Using the language of relative states and (5.4), (5.5)one can express the total system $S+E$ as being in a superposition of the eigenstates belonging to an observable of S and the relative states of the environment with regards to the eigenstates. More precisely, say that system S has an observable with eigenstates $\{\phi_i\}$, and that the environment was described by ψ_E, then when the system and environment interact

$$\psi^{S+E} = \psi_E \sum_i a_i \phi_i = \sum_i a_i \phi_i \psi_E (\text{rel } \phi_i | S) \qquad . \tag{5.15}$$

The relative states of the environment have many degrees of freedom, therefore the relative states will be orthogonal, expressing isolated environments that cannot interact with each other, which is interpreted as different worlds [24].

When an observer performs measurements on a quantum system, he or she is letting the system interact with the environment before he or she can make an observation. When a microscopic system interacts with the environment (a macroscopic system), the total wave function can be expressed as a superposition of the observables eigenstates and the relative states of the environment. Each term in the superposition will quickly decohere, with each term representing and isolated world. This happens at such a small timescale, that no observer can make an observation, before decoherence, and afterwards branching of the wave function, has occured [24].

3 The Problem of Probability

Pure wave mechanics is, unlike conventional quantum mechanics, deterministic. The reason for this is because one abandons the collapse postulate and regards systems as part of a larger system, instead of systems being isolated. However, experiments have again and again corroborated the statistical nature of quantum mechanics, which means that the many worlds interpretation needs to be able to explain the statistical nature we observe. In conventional quantum mechanics the statistical nature arises from the collapse of the wavefunction. Furthermore, the nature of probability is different in a deterministic theory versus probability in an indeterministic theory, such as conventional quantum mechanics. In the latter, probability is an expression of the theory, a fundamental indeterminism which cannot be removed by more information. In the former, probability seems only to be able to take on two values; 0 or 1. Either an event happens or it does not, each event governed by the theory. However one can assign probability in a deterministic theory in the form of the observer's ignorance. Observers cannot access all information, such as which branch trajectory they are on, which gives rise to the seemingly statistical nature, from the point of view of the observer. Thinking of probability arising from the observer's ignorance in the many worlds interpretation, still does not solve everything. A simple way of introducing probability into the many worlds interpretation through ignorance, is simply by counting the branches with the relevant eigenstate and comparing it to the total number of states. This, however, assumes that every outcome is equally probable, which is not what we observe for a general quantum system. The problem here is basically how to quantify our ignorance, how does one create a measure for different outcomes [45].

Both Everett and DeWitt circumvent this problem by postulating that each branch of the total wave function has to have a measure, which they argue must be the square modulus of the coefficients in the total superposition, e.g. the probability of observing system S_1 in the eigenstate ϕ_i in (5.10) is givin by $P(\phi_i) = |a_i|^2$. This argument, however, has been criticised as being circular: One introduces probability with the intention to derive probability. Furthermore, there are no arguments to why a measure needs to be introduced, other than to give the theory the correct statistical nature [20] [21] [22].

The problem of probability in the many worlds interpretation is one the biggest objections towards it. Introducing a measure for each branch is to make the interpretation fit the data, not an introduction motivated trough theoretical arguments, thus, it seems unsatisfying. This measure, though, obeys the laws of probabilities and symmetry and thus seems a natural choice, at least that is what some adherents of the Everett interpretation would argue [19]. There have been attempts to derive the Born rule from the Everett interpretation through various schemes. First of all probability in the Everett scheme is different from conventional quantum mechanics, because the probability in conventional quantum mechanics stems from the indeterminism of the theory. In the Everett interpretation, however, the theory is a deterministic theory and the probability relates to the observer's ignorance. The probability in the many worlds interpretation, thus, has a more subjective nature.

Probabilities, then, are related to agents and their knowledge. David Deutsch has taken an approach based on decision theory, where the probabilities are assigned by agents in a world where they expect probabilities to behave according to conventional mechanics, and is thus able to derive the Born rule [19] [45]. This approach has even been said to be an approach that reverses the problem, by using the many worlds interpretation to define probability, a troubled concept in philosophy [49].

Sean Caroll and Charles Sebens have used the concept of *self locating uncertainty*, a concept from the realm of cosmology, which enters at the moment after the world has split, but before the observer has been made aware of the result of his or her measurement. At this moment the observer does not yet know which branch he or she is on, and there is therefore an uncertainty regarding the observer's position on the universal wave function, i.e on which branch of the universal wave function. This approach only works for rational probabilities however [24].

A last note on probability is that in the Copenhagen interpretation, there is no derivation of the Born rule it is postulated, and is not a natural conclusion of the theory.

4 Objections to the Many Worlds Interpretation

This section provides some of the most common objections to the many worlds interpretation, as well as the possible rebuttals from the point of view of a many worlds interpretation's proponent.

4.1 Conservation of Energy

- Since the branching of the wave function is interpreted as the world splitting, new matter is created since one worlds becomes two, which must be clear violation of energy conservation.

The many worlds proponent would argue that the energy from an observer's point of view does not change. So violation of energy conservation occurs, since any observer shares his or hers trajectory with the world they observe. Furthermore, the Universe is, in the many worlds interpretation, in a superposition of energy eigenstates, so the energy of the Universe is ill-defined and the question of what the energy of the Universe is, becomes meaningless. If what is meant by energy, is the expectation value of the total wave function, then there is no problem, since the energy of each eigenstate is weighted with its coefficient.

4.2 Ockhams Raxor

- Ockham's razor states that given two theories or hypotheses, that both predict the correct results, the most simple should be the preferred one. The many worlds interpretation introduces much more structure into quantum mechanics, than the Copenhagen interpretation. Therefore the many worlds interpretation should be discarded.

The complexity or additional structure referred to in this objection, relates to the dimensions of the Hilbert space describing the universal wave function. However, in conventional quantum mechanics, the Hilbert space for the wave function of a composite system, must have a high enough dimensionality to incorporate the product of the superpositions of each state, since they in general will not be in a definitive state. Only when an observer performs a measurement, does the structure of the superposition, become a definitive state, but the Hilbert space still needs to have a high enough dimensionality to handle the general state. Because of this, the Hilbert space already has "room" enough for many worlds, it is only that in conventional quantum mechanics that the system collapses when measurement is performed, so the state vector simplifies, but the Hilbert space has the same dimensionality as it would in the many worlds interpretation [24].

The many worlds interpretation has the appeal of being a more consistent interpretation of quantum mechanics, removing some of the paradoxes associated with the Copenhagen interpretation and solving the measurement problem. It also appeals to those who value determinism in a theory and that the theory should give a representation of nature itself, not just of our knowledge of nature. It can, furthermore, be regarded as the simplest interpretation, since it assumes nothing but the wave function and the wave equation. The biggest problem is how it handles probability.

Chapter 6

Bohmian Mechanics

When Einstein, Podolsky and Rosen published their article, presenting the EPR-paradox, it was with the motive to show that quantum mechanics is incomplete and that some hidden variables must exist, which specify the system further. At the time of this proposal there were no hidden variables theories, it was merely a hypothesized theory. In the 1920s though, during the conception of quantum mechanics, Louis de Broglie had formulated the pilot-wave theory, where a wave guides a particle. He presented his theory at the 5th Solvay Conference in 1927, but it was met with scepticism, and was not awarded much attention afterwards, so de Broglie abandoned the theory. However, more than 20 years after his presentation, de Broglie's theory lead to a hidden variables approach of quantum mechanics, but not the one the authors of the EPR-paper had in mind[1]. David Bohm picked up the theory in 1951 and in his own word "followed de Broglie line of thought to the end" [27] by creating a coherent theory which is today known as bohmian Mechanics or the de Broglie pilot wave theory. There are slight differences between the two approaches, and the presentation here is based on the approach of Bohm.

Bohmian mechanics takes an explicit particle picture. Particles such as the electron exist at all times, and the question of where the electron is in its orbit around the atomic nucleus, makes complete sense. The theory is nonlocal and therefore not affected by Bell's inequality since it assumes locality in its derivation. The hidden variables are the exact positions of the particles in question. The theory is consistent with quantum mechanics and reduces to classical mechanics in the limit[2] $\hbar \to 0$.

The theory uses the wave equation to specify the evolution of the pilot wave. Schrödinger's equation is a non-relativistic equation, but the theory can be extended to the relativistic regime and quantum field theories with bohmian mechanics have been formulated. This pilot wave guides the particle through *the guidance equation.* Unlike the many worlds interpretation, bohmian mechanics adds new physics to quantum mechanics when it assumes the guidance equation.

This section gives an insight to bohmian mechanics and its key elements, such as the quantum potential and the guiding equation. It will give a very brief description of the differences between the pilot-wave theory of de Broglie and the mechanics of Bohm.

[1]Einstein was indeed a sceptic of bohmian mechanics [26]

[2]This limit corresponds to the spacing of quanta approaching zero.

1 Formalism

1.1 Reinterpreting the Schrödinger Equation

The starting point of bohmian mechanics is to rewrite the Schrödinger equation for one particle [27] [30].

$$i\hbar\frac{\partial\psi}{\partial t} = \frac{\hbar^2}{2m}\nabla^2\psi + V\psi. \tag{6.1}$$

The wave function can be rewritten, so it is described by the functions $R(\mathbf{x},t)$ and $S(\mathbf{x},t)$ through $\psi = R\,\exp\left(\frac{i}{\hbar}S\right)$, where the dependence on variables have been suppressed, as will be done throughout. With this description of the wave function the Schrödinger equation can be used to formulate equations for R and S. Notice that then $\nabla^2\psi$ is given by

$$\begin{aligned}\nabla^2 R\,\exp\left(\frac{i}{\hbar}S\right) =& \exp\left(\frac{i}{\hbar}S\right)\nabla^2 R + i\frac{1}{\hbar}\exp\left(\frac{i}{\hbar}S\right)2\nabla R\nabla S \\ &+ i\frac{1}{\hbar}\exp\left(\frac{i}{\hbar}S\right)R\nabla^2 S - \frac{1}{\hbar^2}\exp\left(\frac{i}{\hbar}S\right)R\left(\nabla S\right)^2. \end{aligned}\tag{6.2}$$

The time derivative of the wave function becomes

$$\frac{\partial\psi}{\partial t} = \frac{\partial R}{\partial t}\exp\left(\frac{i}{\hbar}S\right) + \frac{i}{\hbar}R\frac{\partial S}{\partial t}\exp\left(\frac{i}{\hbar}S\right). \tag{6.3}$$

Inserting (6.2) and (6.3) in (6.1), dividing by $\exp\left(\frac{i}{\hbar}S\right)$ and arranging the real and imaginary terms, one is left with

$$-R\frac{\partial S}{\partial t} + i\hbar\frac{\partial R}{\partial t} = -\frac{\hbar^2}{2m}\left(\nabla^2 R - \frac{1}{\hbar^2}R\left(\nabla S\right)^2\right) + RV + i\frac{\hbar}{2m}\left(2\nabla R\nabla S + R\nabla^2 S\right). \tag{6.4}$$

Splitting the equation into a real and an imaginary part

$$\frac{\partial S}{\partial t} = -\left(\frac{\left(\nabla S\right)^2}{2m} + V - \frac{\hbar^2}{2m}\frac{\nabla^2 R}{R}\right), \tag{6.5}$$

$$\frac{\partial R}{\partial t} = -\frac{1}{2m}\left(R\nabla^2 S + 2\nabla R\nabla S\right). \tag{6.6}$$

These equations, (6.5) and (6.6), highlight certain characteristics of the wave function. To further see this, equation (6.6) can be expressed more compactly by

$$\frac{\partial R^2}{\partial t} = -\nabla\left(R^2\frac{\nabla S}{m}\right). \tag{6.7}$$

In the classical limit, $\hbar \to 0$, equation (6.5) reduces to the Hamilton-Jacobi equation of classical mechanics

$$\frac{\partial S}{\partial t} + H = 0, \tag{6.8}$$

where the phase of the wave function S, behaves as the classical action [27] [30]. Equation (6.5) highlights, what the correspondence principle tried to ensure in quantum mechanics, a link between classical physics and quantum physics. Therefore (6.5) can be seen as the extension of the Hamilton-Jacobi (6.8) to microscopic systems, where the quantum postulate cannot be ignored.

With (6.14) established it is noticed that in (6.7) the term $\frac{\nabla S}{m}$ represents the velocity. By defining $P = R^2$, equation (6.7) can be written as

$$\frac{\partial P}{\partial t} + \nabla(P\mathbf{v}) = 0. \tag{6.9}$$

This equation shows that the change in P at one point in phase space, equals the rate leaving the point. This is consistent with probability and the equation shows that P behaves as a probability [27] [30]. Other quantities could abide by (6.9), and indeed it is argued that P does not necessarily have a relation to probability in bohmian mechanics and can be thought as independent. However, under most circumstances it acts as the probability [30, chapter 3, p 41]. To higlight how this comes about, assume that P is related to the probability, ρ by $P = \rho F$. Since both P and ρ satisfy (6.9), it can be deducted that F must satisfy

$$\frac{\partial F}{\partial t} + \mathbf{v}\nabla F = 0. \tag{6.10}$$

The left hand side of (6.10) corresponds to the overall rate of change of F, that is $\frac{dF}{dt}$. Since this rate equals zero, F must be a constant of motion, i.e. F describes a quantity of a particle that does not change in time, but it could change in configuration space. Regard an element of configuration space, $\Delta\Omega$, containing several particles in different configurations. The element is chosen sufficiently small, so that F can be regarded as constant of the element. To show that P corresponds to the probability, F must be shown to not only be a constant of motion, but a constant over all of configuration space, which is seen by tracing the particle trajectories contained in $\Delta\Omega$. The central property to do this, is that the guidance equation (6.14) in general admits violent and chaotic motions. Thus particles starting in the element $\Delta\Omega$ will therefore have trajectories that make them cross all of configuration space. The element $\Delta\Omega$ will therefore grow as thread like structure through all of configuration space, and since F is constant over the element $\Delta\Omega$, it must be a constant of all configuration space, and just a constant. Then P can be regarded as the probability[3] [30].

1.2 The Quantum Potential

Equation (6.5) can be regarded as an extension of the Hamilton-Jacobi equation. To follow this line of thought, the last term in (6.5) is named Q

$$Q = -\frac{\hbar^2}{2m}\frac{\nabla^2 R}{R}. \tag{6.11}$$

Equation (6.5) can then be expressed as

[3]For a more mathematical and general derivation one is referred to [30, chapter 9.3]

$$\frac{\partial S}{\partial t} = -\left(\frac{p^2}{2m} + V + Q.\right). \tag{6.12}$$

Regarding (6.12) and using the classical Hamilton Jacobi equation as an analogy, the term Q can be viewed as another energy term in the Hamiltonian. This term, Q, is dubbed *the quantum potential* [27] [30].

The quantum potential is an all-pervasive potential that every particle feels, and is associated with R, which further is associated with the wave function. This means that every particle, even free particles, can be thought to experience a quantum force ∇Q acting on them. Moreover since the quantum potential has R in its numerator and denominator, the quantum potential does not depend on the size of R only of its form

$$R \to kR \qquad -\frac{\hbar^2}{2m}\frac{\nabla^2 R}{R} \to -\frac{\hbar^2}{2m}\frac{\nabla^2 kR}{kR} = -\frac{\hbar^2}{2m}\frac{k\nabla^2 R}{kR} = -\frac{\hbar^2}{2m}\frac{\nabla^2 R}{R}.$$

The strength of the quantum potential is independent of the intensity of ψ. This novel feature seems at first to be completely incompatible with classical mechanics, e.g. the energy transmitted to an object from a shock wave is certainly correlated with the size of the shock wave and not its form. This feature will be examined further in a later section.

1.3 The guidance equation

By demanding that the wave function ψ should be a single valued function, the following constraint is reached

$$\oint \mathbf{p}\, d\mathbf{q} = n\hbar. \tag{6.13}$$

This is the Bohr-Sommerfeld condition. The constraint can be satisfied by demanding that the gradient of the phase belonging to the wave function is the momentum [27] [30].

$$\mathbf{p} = \nabla S. \tag{6.14}$$

This is the guidance equation and is not only necessary to ensure that the wave function only has one value, but is a necessity for the assumption that particles are well-defined at all times, because it specifies how the wave guides the particle. Other relations between the momentum of the particle and S can been chosen, so to specify other guidance relations [27], but (6.14) seems almost natural if S is regarded as the action, as implied by (6.5), since the guidance equation would merely restate a known classical relation [48]. The guidance equation can also be motivated from symmetry considerations [32]. The guidance equation relates the momentum of the particle to the phase of the wave function, but it can also be directly related to the wave function itself. From the guidance equation one can see that $v = \frac{\nabla S}{m}$. Generalizing this to configuration coordinates Q

$$\frac{\partial Q}{\partial t} = \frac{\nabla S}{m}, \tag{6.15}$$

and noting that

$$\frac{\nabla\psi}{\psi} = \frac{\frac{i}{\hbar}\nabla S\, R\exp\left(\frac{i}{\hbar}S\right) + \nabla R\,\exp\left(\frac{i}{\hbar}S\right)}{R\exp\left(\frac{i}{\hbar}S\right)} = \frac{i\nabla S}{\hbar} + \frac{\nabla R}{R},$$

enables the guidance equation to be expressed in terms of the wave function

$$\frac{\partial Q}{\partial t} = \frac{\hbar}{m}\mathrm{Im}\frac{\nabla\psi}{\psi}. \tag{6.16}$$

This version of the guidance equation was presented in De Broglies paper "The double solution". It enables one to find the trajectories of the particles, from the wave function of the system. The picture in bohmian mechanics is thus, that every particle is accompanied by a wave or field ψ, which evolves deterministically through the Schrödinger equation. The particles trajectories are then given by the guidance equation. The statistical behaviour that we observe therefore relates to the fact that we never exactly know where the particles are to begin with, and the square modulus of the wave function acts as the probability of finding them at a given position.

2 Metaphysical Interpretations

2.1 Quantum Force and Active Information

Regarding the quantum potential, Newtons second law can be cast in a quantum form

$$m\frac{d^2x}{dt^2} = -\nabla(V + Q). \tag{6.17}$$

In terms of force there are then two distinct forces acting on a particle: One from the regular potential V, which we are familiar with from classical mechanics, and one from the quantum potential Q, which is the source of quantum behaviour [27] [30].

In the formalism of Bohmian mechanics, every particle is accompanied by a field ψ, which establishes a quantum force. E.g. in the double slit experiment, the particle moves through one of the slits, but the field ψ moves through both slits and creates an interference pattern. This pattern establishes a quantum force, that exerts its influence on the particle, which in turn creates particle trajectories that exactly corresponds to the well known interference pattern observed and predicted by quantum mechanics.

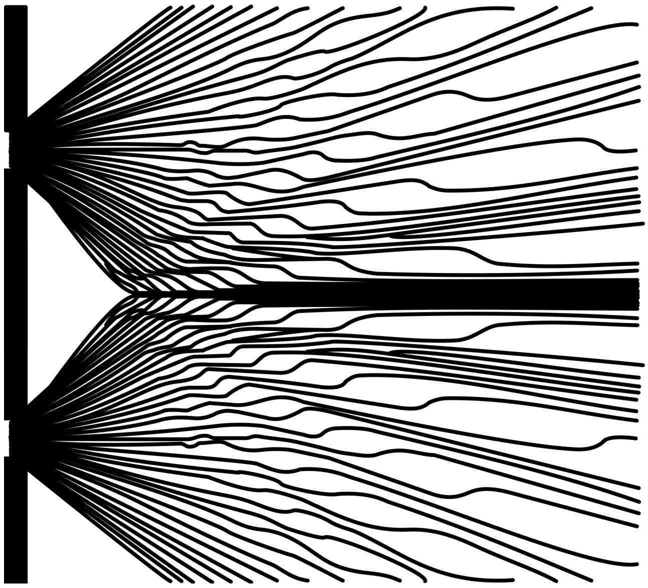

Figure 2: Bohmian particle trajectories for the double slit experiment. Each trajectory corresponds to a certain initial configuration, which are the "hidden variable" in bohmian mechanics.

Each trajectory corresponds to a certain initial configuration coordinate of the particles. These are the so-called "hidden variables" in the theory, which is somewhat of a misnomer, since it is not a new physical property which one might infer from the term. In this sense bohmian mechanics seems in line with the remarks that Heisenberg made when he presented his uncertainty relation:

However in the strong formulation of the causal law 'If we know exactly the present, we can predict the future' it is not the conclusion but rather the premise which is false. We can not know as a matter of principle, the present in all details... [10, p 331]

Bohmian mechanics is an interpretation that embraces this notion, and gives it rigour through a mathematical formalism.

The quantum force is a novel concept and some of its features at first seem very different from anything in classical physics. As noted earlier the quantum potential does not depend on the strength of the field ψ, which in turn means that the quantum force does not depend on it. This means that the quantum force does not diminish with distance, e.g. in the double slit experiment the quantum force has the same strength independent of the distance from the slits, so the interference remains unaltered when the detectors are moved further away from the slits. The quantum force is not a mechanical force as known from Newtonian mechanics [30]. This renunciation of the of a mechanical force bares a resemblance of Bohr's answer to the EPR-paradox to be presented later, and seems as a way to set the nonlocality of bohmian mechanics on par of that of the Copenhagen interpretation. Indeed it is worth noting that Bohm did not specify this nature of the quantum force in his original paper, but only in a book more than 40 years later.

To illustrate the nature of the quantum force regard a free particle. By definition a free particle must have $V = 0$, but since every particle is accompanied by a field ψ the quantum potential is nonzero and therefore the quantum force is nonzero as well. This implies that free particles do not move in straight lines, which is illustrated in the trajectories of the double slit experiment. Furthermore since the quantum potential is independent of the strength of the ψ, it seems as small energies can produce significant changes, which again is a radical departure from classical physics. However, ψ should not be interpreted as a field that causes the particle to follow a certain trajectory, it should rather be thought of as field that informs the particle how it should move. This concept is dubbed *active information* [30, chapter 3, p 35]. An analogy of the concept of active information can be found by regarding radio waves to a remote controlled vessel. The low intensity radio waves makes the vessel change its direction, but the change in direction is not powered by the radio waves, it comes from the vessels own power supply. The radio waves merely informs the vessel how to distribute its power. Such examples are not limited to man-made devices, but also show up in biology in the form of chemical coding. Certain proteins code for production of certain biologic entities without supplying the energy for this production. DNA codes for the production of various types of cells and cytokins are exchanged between cells as signals, e.g. when cells are communicating the discovery of a virus and needs to produce T-cells to combat the virus. Here the proteins plays the role of providing active information to other cells [30]. The notion of active information does not play a role in the mathematical formalism, but only serves an role in regards to the interpretation. Indeed the following is remarked by Bohm and Hiley in their book concerning bohmian mechanics.

Of course in a purely logical sense, the theory could be said to be defined without this notion and could, of course, be thus expressed in a logically consistent way. But it is a key part of our intention in this book to help make the theory more intelligible in an intuitive sense, and not merely regard it as a system of equations from which could be derived algorithms permitting a calculation of interesting results. We feel that at least something like the notion of active information would be needed in any attempt to do this; e.g. to account for quantum interference and the peculiar nonlocal properties of the many-body system in an intuitively understandable way. [30, chapter 4, p 60]

The concept of active information brings some very novel features with it. The above examples all involve entities with substructure decoding the information, however the active information in Bohmian mechanics is to be decoded by elementary particles such as the electron. The theory thus implies that particles such as the electron must have some substructure to process the information provided by the field ψ. This notion is a departure from the established thinking in physics; the behaviour of particles should become simpler the smaller particles get. However one can liken the behaviour of particles to that of a crowd. The behaviour of the whole crowd can be quite simple to describe, while a certain member is very complex entity [30, chapter 3, p 37]. Again these notions are not in the original paper of Bohm describing bohmian mechanics, therefore they are not part of the mainstream understanding of bohmian mechanics, but do imply how Bohm himself thought of the theory. This last notion of substructure, does imply that active information was not only inserted to the theory to try an make the nonlocal effects more easy to digest, since it needs the particles to have substructure, which would not be easily digested by physicists.

2.2 De Broglie's Pilot Wave

Bohmian mechanics is a continuation of the work done by Louis De Broglie on his idea of a so-called *pilot wave* that guides the particle. The pilot wave is not the same wave as the known wave function, ψ from standard quantum mechanics. The pilot wave is a physical wave, which is accompanied by a probability wave ψ. The pilot wave has a small area of high amplitude[4], which corresponds to the location of the particle. Outside this area the wave has a small amplitude. The physical wave u can therefore be described by

$$u = u_0 + v, \tag{6.18}$$

where u_0 represents the particle, i.e. the high amplitude, while v represents the weak part of the wave, which occupies all the domain of the u wave [31].

The following quote from de Broglie's article highlights some of his central thoughts concerning the pilot-wave theory

It [u_0] defines the particle's internal structure. We wil not insist on this point the study which at the time being seems premature... since the publication of Schrödinger's works in 1926, it became customary to only consider the ψ wave, of arbitrarily normed amplitude. But this wave cannot be considered as a physical wave... because the amplitude of a physical has a well determined value, and cannot be arbitrarily normed... One is therefore led to consider the ψ wave as probability representation, a simple prediction instrument, permitting a forecast of the possible measurement results of physical quantities belonging to a particle or to an ensemble of particles. It is however impossible for a simple probability representation to create physical phenomena such as the local observation of a particle, or to impose definite values to energies of atomic stationary states. Objective reality only, may give such effects, and a probability representation has no such character... It is nevertheless unquestionable that use of the ψ wave and its generalization did lead to accurate prediction and fruitful theories. This is an indisputable fact. The situation is clarified by introducing together with the statistical ψ wave, the v wave, which being an objective physical reality may give rise to phenomena the statistical aspect of which is given by the ψ wave. [31]

The paragraph suggest that De Broglie did not consider the wave function as an ontic entity and wanted this of his new theory. He therefore incorporated a physical wave, the pilot wave, in his theory, which harboured the particle in a small region. Furthermore this particle would have some inner structure represented by u_0. Furthermore, De Broglie also hypothesized that elementary particles have an internal clock with an associated frequency. The particles are thus vibrating in the pilot wave, which he showed to have the same phase as the physical wave v [31]. Thus both Bohm and de Broglie stress the need for substructure in their respective theories, and the internal clock referenced by De Broglie can be thought to relate to the processing of information implied by Bohm and Hiley.

To find the trajectory of the particle, then one has to have the statistical wave ψ and the physical wave v of the system. The statistical wave can be found through the Schrödinger equation, while the physical wave, and thus the particle, could be found through the guidance equation. Because one needs to find a solution to both these equations, De Broglie originally named his theory *the double solution theory.*

The double solution theory is based on equations that handle the statistical wave ψ and the physical wave v. However the high amplitude area, or singularity, represented by u_0 is not handled in either of these equations. The particle's substructure is entailed in u_0, so being able to formulate a theory concerning this area would make one able to draw

[4] In first approximation the high amplitude can be considered a singularity

conclusion concerning the substructure. De Broglie contemplated that the singularity must be governed by a non-linear equation, which for small amplitudes can be approximated to a linear equation such as the ones ψ and v obey. How exactly this non-linear equation would look, De Broglie leaves in the unknown, since it concerns the inner structure of the particle, a subject that De Broglie feels is premature to discuss.

3 Further features of Bohmian Formalism

3.1 Many-Body System and Nonlocality

Consider a two-body system, where the particles will be indexed by i and j. The wave function for the whole system can again be written in terms of an amplitude R and a phase S, i.e. $\Psi(\mathbf{x}_i, \mathbf{x}_j, t) = R(\mathbf{x}_i, \mathbf{x}_j, t) \exp\left(\frac{i}{\hbar} S(\mathbf{x}_i, \mathbf{x}_j, t)\right)$. Then the Schrödinger equation can be formulated as the two following equations

$$\frac{\partial S}{\partial t} + \frac{(\nabla_i S)^2}{2m} + \frac{(\nabla_j S)^2}{2m} - \frac{\hbar^2}{2m} \frac{(\nabla_i^2 + \nabla_j^2) R}{R} + V = 0, \tag{6.19}$$

$$\frac{\partial P}{\partial t} + \nabla_i (P \mathbf{v}_i) + \nabla_j (P \mathbf{v}_j) = 0, \tag{6.20}$$

with $P = R^2$ and

$$p_i = \nabla_i S \qquad \wedge \qquad p_j = \nabla_j S. \tag{6.21}$$

From (6.19) it is seen that the quantum potential for the whole system, depends and the coordinates of each of the particles. Furthermore the guidance relation for each particle is specified by the phase of the whole system. The two particles are thus correlated, and because the quantum potential depends on the form, and not the amplitude, of Ψ, it does not necessarily fall off with distance [30]. This means that two particles can depend strongly on each other even over great distances. This is the nonlocality of the interpretation. Nonlocality is regarded as an almost unacceptable feature in physics. Bohm and Hiley notes the following of the feature in bohmian mechanics.

For several centuries, there has been a strong feeling that nonlocal theories are not acceptable in physics. It is well known for example, that Newton felt very uneasy about action-at-a-distance and that Einstein regarded it as 'spooky'. One can understand this feeling, but if one reflects deeply and seriously on this subject one can see nothing basically irrational about such an idea. Rather it seems to be most reasonable to keep an open mind on the subject and therefore allow oneself to explore this possibility. If the price of avoiding nonlocality is to make an intuitive explanation impossible, one has to ask whether the cost is not too great. [30, chapter 4, p 57]

The objection of nonlocality is dismissed as irrational, and that by allowing the theory to be nonlocal one can formulate an intuitive explanation[5]. A particular reason why physicist are so squeamish about nonlocality is because according to relativity, superluminal messages move backwards in time thus breaking causality [3, chapter 12]. This problem

[5] "Unlike regular quantum mechanics", one might claim is written between the lines

has been treated and shown not to cause any inconsistencies in the relativistic extension of the theory[6] [30].

Another novel feature of the theory is that the particle interaction does not solely depend on their respective distance from each other, but also on the orientation; specifically the interaction does not only depend on r, but also θ and ϕ. This feature implies that one cannot regard parts of a system, but needs to regard the system as a whole. Extrapolating this notion leads to a rather disturbing realization; that one can never regard a small system alone, but one needs to regard the complete system, which would be the complete Universe! However for a system of two particles where the total wave function can be written as a product of two functions, each depending on the coordinates to one particle

$$\Psi(\mathbf{x}_i, \mathbf{x}_j, t) = \phi(\mathbf{x}_i, t) \cdot \phi(\mathbf{x}_j, t), \tag{6.22}$$

the quantum potential Q can be written as

$$Q(\mathbf{x}_i, \mathbf{x}_j, t) = Q_i(\mathbf{x}_i, t) + Q_j(\mathbf{x}_j, t) \tag{6.23}$$

with

$$Q_i(\mathbf{x}_i, t) = -\frac{\hbar^2}{2m}\frac{\nabla_i^2 R_i(\mathbf{x}_j)}{R_i(\mathbf{x}_i, t)} \qquad \wedge \qquad Q_j(\mathbf{x}_j, t) = -\frac{\hbar^2}{2m}\frac{\nabla_j^2 R_j(\mathbf{x}_j)}{R_j(\mathbf{x}_j, t)}. \tag{6.24}$$

In this case then, the quantum potential, and thus the particles, behave independently of each other. Such cases arises naturally in parts of Universe where decoherence occurs. So when regarding large enough parts of the Universe, that is large enough that decoherence sets in, the parts behave independently of each other, and there is no need to regard the whole Universe to examine a smaller system. This also highlights how in the classical limit the nonlocal interactions vanish [30].

3.2 Measurement

The measurement process in bohmian mchanics, is treated as in the many worlds interpretation. The system of interest and measuring apparatus are both treated as quantum systems, and when measurements are performed the wave functions become entangled. In standard quantum mechanics one would say that neither system is in a definitive state, when the systems are entangled. However, in bohmian mechanics both systems have well-defined physical observables at all times. The fact that the systems do not have a definitive state in standard quantum mechanics, is translated to very violent and rapid behaviour of the systems in bohmian mechanics. The systems move very rapidly through phase space. While the systems are entangled the wave function of the composite system can be expressed as a superposition of relative states, as in (5.4) and (5.5). This superposition can be thought of a superposition of the pointer states of the apparatus and their relative states. The terms in this superposition are not orthogonal in the beginning of the interaction of the apparatus and system, i.e. the measurement. When a measurement is performed on a system, however, it will interact with the environment, and decoherence will set in, making the terms in the superposition mutually orthogonal and suppressing interference between them. Thus the systems become locked in phase space with well-defined physical observables corresponding to a specific term in the superposition. This process is what causes

[6]This point is rather significant, but because of the purpose and size limitations of the thesis it could unfortunately not be included. The reader is referred to the original book of Bohm & Hiley

the apparent collapse of the wave function. In this sense measurement is much the same in bohmian mechanics as in the many worlds interpretation: All the branching structure still occurs during interactions, but the initial conditions and the guidance equations picks one particular the branch.

4 Objections to Bohmian Mechanics

This section focuses on some of the objections raised in regards to bohmian mechanics. Some of the objections raised are mostly based on ignorance, e.g. a limited knowledge of Bell's inequality, but are still included since they form some of the more popular objections.

- Bohmian mechanics is untenable, since Bell's inequality shows that hidden variable theories are impossible.

  Bell's inequality assumes locality, so Bohmian mechanics is exempt, since the theory is nonlocal[7].

- Bohmian mechanics is not a distinct theory from the Copenhagen interpretation, since it produces the exact same outcomes and cannot be verified experimentally.

  This objection treats bohmian mechanics as a theory, not as an alternative interpretation of quantum mechanics. Furthermore it presumes that the first established theory should only be replaced by a new theory, if it predicts new physical phenomena, even though the new physical theory might be simpler, more intuitive and therefore easier to communicate. This might not necessarily be the case with Bohmian mechanics, but the theory should not be discarded on lone basis that it did not come first[8]. Indeed it is quite intriguing what might have happened, had De Broglie not abandoned his pilot wave theory in 1927; bohmian mechanics might have been the conventional interpretation of quantum mechanics.

- Bohmian mechanics is not a viable theory because it is nonlocal

  The EPR paradox uses the notion of nonlocality as an argument to show that quantum mechanics is an incomplete theory. In this same sense it can be used to argue against Bohmian mechanics. It would not make much sense, though, to use nonlocality as an argument against Bohmian mechanics, while still preferring the Copenhagen interpretation, which is nonlocal as well. The nonlocal nature of the theory is, however, much more explicit in Bohmian mechanincs, then in the Copenhagen interpretation. Furthermore quantum mechanics can be regarded as epistemic theory in the Copenhagen interpretation, unlike in Bohmian mechanics where it is an ontic theory. The argument seems stronger used in relation to preferring a local interpretation of quantum mechanics, such as the many worlds interpretation, over Bohmian mechanics. However even in this instance one could justly ask what is wrong with nonlocality? The theory has been extended to incorporate special relativity and been shown still not to contain any inconsistencies.

- Bohmian mechanics unnecessarily removes a symmetry from the formulation of quantum mechanics

[7] Bell himself was actually a proponent of Bohmian mechanics.

[8] In practice history however shows that prevalent and accepted theories are not easily abandoned.

This objection is related to the fact that the formalism of quantum mechanics allows one the freedom to choose whether one wants to work in momentum space or position space. This freedom is removed in Bohmian mechanics, where the statistical distribution is of the position. Furthermore it can be shown that ascribing a definite value to a dynamical variable at all times, comes at the price of removing a symmetry such as the $q \leftrightarrow p$. A theory like Bohmian mechanics cannot be formulated without removing such a symmetry.

Symmetries plays a very distinguished role in physics[9] and the removal of symmetry without experimental evidence seems as a flaw in the theory. Taking a step back and regarding Hamilton's equations of classical mechanics, one realizes that these equations are invariant under arbitrary canonical transformations, no matter what form the Hamilton takes. Physical symmetries however are only associated with a special class of canonical transformations, that leave the functional form of the Hamilton invariant. Extending this view to quantum mechanics, it is realized that canonical commutation relations are left invariant under arbitrary unitary transformations. Genuine physical symmetries are represented by an operator that commutes with the Hamiltonian. The symmetry removed in bohmian mechanics is thus not a genuine physical symmetry.

Bohm himself answered this very objection by pointing out what the main objective of his formulation of the theory was. It was to show that hidden variables theory are possible, since impossibility proofs had been claimed to exist. His intention was not necessarily to formulate a theory that should surpass quantum mechanics [26].

Bohmian mechanics is an interpretation that does exactly what it sets out to do. It gives a deterministic and more intuitive description of quantum behaviour, at the expense of introducing some quite novel physical features, such as the explicit nonlocality of the interpretation. The main question concerning bohmian mechanics is probably mostly if these novel features, are too high a price to pay? Another question could be if there really is a price to pay at all? Bohmian mechanics solves the measurement problem by rejecting the notion that the wave function gives a complete description of a system, and can give an explanation for the apparent collapse of the wave function.

The collapse of the wave function does not have a mathematical description in standard quantum mechanics, only an ad hoc argument for what it does and when it applies. If it were given a mathematical description, then suddenly the nonlocality of the interpretation becomes explicit just as it is in bohmian mechanics. Furthermore if one were to try explain this nolocal feature as an influence and not a mechanical disturbance, as Bohr, then one is left at the same place as one would be with bohmian mechanics and the notion of active information.

Compared to the many worlds interpretation, bohmian mechanics might seem less complicated. It only supposes the existence of one world and everything in that world can be described by well-defined quantities. Bohmian mechanics does suppose new physics though, which the many worlds interpretation does not, therefore in terms of mathematical structure the many worlds interpretation is simpler, and it preserves the locality of interactions in each world. The metaphysical implications seem much simpler in bohmian

[9] The special role is particularly highlighted in Noether's theorem

mechanics, though, when one considers the existence of particles in one world simpler then the existence of one particle in multiple worlds.

Chapter 7

Comparing the Interpretations

The various interpretations presented here have several properties in which they differ from one another. These properties are what make physicists prefer one interpretation over another, or at least physicists who are engaged in the debate of quantum interpretations. For example bohmian mechanics would appeal to those who desire a deterministic theory along the lines of classical mechanics[1], but who do not hold locality as a sacred concept. Furthermore, bohmian mechanics does not abolish the concepts that are used in classical mechanics in the microscopic realm, only that we cannot know their exact values. An electron does have a definite position and velocity at the same time, when we are not observing the electron. This is achieved by introducing a quantum potential that generally induces violent motions of the particles. Bohmian mechanics, thus, tries to save some of the cherished notions of classical mechanics.

The Copenhagen interpretation does not have a clear formulation, since it is collection of thoughts from various physicists who did not agree on how every element of quantum mechanics should be understood. If one makes the assertion that the Copenhagen interpretation is mostly recognized as Heisenberg understood quantum mechanics, then the Copenhagen interpretation is an epistemological interpretation. In the Copenhagen interpretation, then, one concedes that it is not possible to give a description of nature at the atomic level, and that the concepts we use to describe the world cannot be applied straightforwardly to microscopic systems; the concepts are only defined upon measurement, i.e. when no measurements are performed on the system, the system does not have a well-defined position, momentum, etc. An observation can be thought of as instantiating these concepts, however, not all at the same time, since some of these concepts are regarded as complementary; they are mutually exclusive, but are all needed to give a complete description of the system. Furthermore, the wave function is regarded as a measure of our knowledge or information concerning the system of interest, not as a real physical entity, and can be used to determine the probabilities of the occurrence of certain measurements. The nonlocality displayed by quantum mechanics does, thus, not represent a problem, since this nonlocality does not pertain to the physical world, but only our knowledge.

The many worlds description on the other hand, regards the wave function as a real entity and only assumes the Schrödinger equation. Furthermore, it does not limit quan-

[1]Though the presentation of bohmian mechanics by Bohm himself, gives the impression that bohmian mechanics is an effort to go back to the cherished classical realm, however, the original proposal by de Broglie was presented as a radical departure from classical mechanics. Thus with regards to this appeal it would be important to distinguish between bohmian mechanics and the pilot wave theory, even though they share the same formalism.

tum mechanics to the microscopic realm, but extends the applicability of the theory, to describe everything. Thus there is one universal wave function governing the entire universe according to the Schrödinger equation. When we perform measurements, it is one subsystem that interacts with another, thus an observation in the many-worlds interpretation is merely an interaction between two systems. The question concerning the definition of classical concepts takes on a different character in the many worlds interpretation, than in the Copenhagen interpretation, and bohmian mechanics, since the universal wave function is in a constant superposition, we do, however, not perceive this superposition only the elements constituting the superposition. These elements do have well-defined classical concepts, but only those that are measured, or interacting. The interaction chooses what base, i.e. what eigenstates the branching of the universal wave function occurs in. In the Copenhagen interpretation, classical concepts are not considered well-defined, because they are described by a superposition, which according to the Copenhagen interpretation does not make sense, and therefore these concepts cannot be well-defined. However, superpositions are considered real in the many worlds interpretation, where each term is interpreted as a world, and therefore classical concepts are defined in terms of superposition, but we cannot perceive these superpositions, only each term.

To further illustrate the differences and properties of each interpretation, two famous paradoxes will be regarded in the following sections, and the solution to each paradox according to the three interpretations will be presented.

1 Taming Schrödinger's Cat

Schrödinger's cat was introduced in 1.6, the various solutions to the paradox according to the different interpretations will be presented.

The Copenhagen interpretation is associated with observer induced collapse from the presentation of Von Neumann, which was exactly what Schrödinger was objecting to in contemplating the paradox. However, Heisenberg and others did not view the wave function as a physical real quantity, so the superposition does not describe an element of physical reality, therefore, there can be no problem. This conflicts with the apparent interference phenomenon observed in quantum systems, which indicate that the wave function does have some element in reality. Another way to solve the paradox in the, or rather one of the, Copenhagen interpretation(s) is to say that quantum mechanics only describes microscopic systems, but this then raises the question concerning the limit of applicability of quantum mechanics. Decoherence presents a solution to this question, but decoherence only removes the interference terms of the combined superposition, thus, applying quantum mechanics would still leave the cat in a superposition of a dead and alive state. Schrödinger's cat only poses a problem for quantum fundamentalist, that take the wave function as representing a real entity and believe that the wave function collapses when a observer makes a measurement, or they would be inclined to say, that the cat is actually in a superposition of a dead and an alive state. This, however, creates the problem of what exactly is an observer? And furthermore the problem of Von Neumann's infinite regression would arise. As has been explored earlier, Bohr did not believe that the observer induced a collapse in the wave function. In Bohr's mind it was the interaction between the system and apparatus that was central in making the property of decay or non-decayed well-defined. Thus, when the Geiger-counter interacts with the nucleus, the superposition no longer describes the particle and it, as well as the cat, is in a well-defined state [43].

Bohr never gave a clear and strict description of the physical process of defining properties though. The Copenhagen interpretations present various solutions, but all have caveats.

The many-worlds interpretation simply handles Schrödinger's cat, by implying that when the Geiger-counter interacts with the nucleus, a splitting of worlds occurs; one in which the nucleus has decayed and therefore the cat is dead, and one in which the nucleus has not decayed and therefore the cat is alive. The cat would therefore never be in a mixture of dead and alive. Of course the problem of predicting the right probabilities occurs in the many-worlds interpretation, if one does not accept the proposed derivations of the Born rule. Even in this case supporters of the interpretation could say that one assumes the Born-rule as a measure of existence and that we experience this measure as probability, since it abides by the law we have formulated for probability [19].

In **bohmian mechanics** the wave function is only a probability wave and does not give complete description of the system. The state of the nucleus is either decayed or non-decayed, therefore, the state of the cat is either dead or alive not in a mixture of both. The guidance equation and the configuration of the system, determines which state the system is in. When the wave function is described as a superposition of different states, the system can undergo very rapid and violent movements in phase space, because of the quantum potential according to bohmian mechanics. This seemingly could permit a transition from a decayed state to a non-decayed state, which would mean that the cat could make a transition from a dead to an alive state. However, the rapid movement in phase space becomes locked when decoherence sets in, and because the cat is macroscopic system, this will happen very fast. Once the cat dies, the dead state will quickly diverge from the alive state in configuration space, and because of decoherence a transition will not be possible [29].

2 Resolution of the EPR Paradox

The EPR paradox is often labelled as Einstein strongest attack on quantum mechanics and in hindsight also made a significant impact on physics; the suggested hidden variables theory was conceived by Bohm, though de Broglie had established the basis of the formulation years before the EPR-paper, and it was also the starting point of Bell's inequality. Furthermore, the argument had a great impact on Bohr and the language he used to describe his concept of complementarity. **The Copenhagen interpretations**[2] looked to Bohr to answer the EPR-argument. Bohr's response became the standard way of handling the EPR-argument in the Copenhagen interpretations. Bohr focused on the criterion of reality established in the paper, notably the criterion that pertained a physical quantity having an element in reality if it could be measured without disturbing the system, since this contradicts the concept of complementarity. Bohr conceded that there can be no mechanical disturbance[3] between the two separate systems, when measurements are being performed on one of the systems. However, Bohr describes an influence between the two systems on the conditions that give rise to prediction, when one system is being measured. Concretely, using Bohm's example of the argument, when one regards the spin components along a direction described by the unit vector **a** one can make predictions of the other particle's component of spin in this direction, however, not along a unit vector different from

[2] Of course the interpretations had not been dubbed at the time of the EPR-paper

[3] The shift in Bohr's description of complementarity involves, among other things, the use of the word "disturbance", which he restrained from using in relation to complementarity after EPR.

a. Thus, one cannot change the state of one system through this influence [47]. This influence is thought to be of a more ephemeral nature, than a mechanical disturbance, and therefore it does not pose any problems with regards to locality. Superluminal velocities can be recorded, for example the dot from a laser beam on the moon can reach superluminal velocitites when one moves the laser pointer on earth, but it does not relate to a velocity of a physical object or interaction. The influence mentioned by Bohr is thought to be of this nature [3].

The many worlds interpretation is a local interpretation. All physical interactions are local, which is the exact reason that decoherence sets in. However, a world is a nonlocal concept, splitting of a world happens instantaneously everywhere, but this is not a physical object either, and can never be observed. Choosing the many worlds interpretation over the Copenhagen interpretation, one substitutes an ephemeral nonlocal influence for an ephemeral nonlocal splitting of a world [45].

The EPR-argument does not really present an issue in **bohmian mechanics** since it is explicitly nonlocal. Thus, when a measurement is performed on one particle, it changes the wave function through an apparent collapse, which changes the field at the position of the other particle instantaneously. The issue of the EPR-paradox is dissolved if one accepts the premise of bohmian mechanics, namely that nature is nonlocal.

Chapter 8

Other interpretations

The focus on interpretations has so far centered on the Copenhagen interpretation, the many-worlds interpretation, and bohmian mechanics. There are a multitude of other interpretations, some of which was offered as an option in the questionnaire. The following section will give a very brief description of each of these interpretations.

1 Quantum Bayesianism

Quantum bayesianism, or QBism, is an epistemological interpretation that interprets the probabilities of the wave function as a Bayesian probability, thus promoting a subjective probability over an objective. Quantum mechanics describes an observer's degree of belief regarding the occurrence of specific events, such as measurement of spin on an electron yielding spin up. Thus, in QBism the wave function is related to the observer, each observer has their own wave function, and quantum mechanics governs the degree of belief. QBism abolishes objective probability for subjective degrees of belief, the ultimate interpretation of Bohr's expression concerning objectivity. Regarding the wave function as an subjective element, and not one that belongs to physical reality, dissolves the problems relating to measurement and nonlocality in standard quantum mechanics [33].

2 Objective Collapse

Collapse approaches to quantum mechanics suggest that the Schrödinger equation should be modified to include a non-linear term that describes the stochastic process of collapse. The approach tries to give a strict mathematical description of the collapse process, unlike in the Copenhagen interpretations. Collapse approaches are thus not merely another interpretation of quantum mechanics, but an all-together different theory. This theory could be falsified, though we do not at the present time have the technology to carry out these experiments [34]. One example of this approach is the spontaneous collapse of Giancarlo Ghiradi, Alberto Rimini and Tullio Weber. A single particle can be in a superposition, but a new phenomenon arises in a system of multiple particles, that makes one particle collapse, which further instigates a collapse of the other particles. The theory of spontaneous collapse gives exactly the same predictions for all microscopic system, but for macroscpic system, specifically macroscopic systems in a superposition, the theory gives different predictions than that of standard quantum mechanics and can therefore be falsified. The theory preserves the indeterminism of the standard formulation, but the

Schrödinger equation becomes quite cumbersome in the theory and it is not symmetric in time [48].

3 Consistent Histories

Consistent histories, also known as decoherent histories, can be thought of as an extension of the Copenhagen interpretation, or rather "Copenhagen done right" according to its adherents. It came to being after the advent of decoherence and uses the concept to define elements at the microscopic level. The interpretation does not place special emphasis on measurement or observer, wave function collapse is abandoned, and resolves the measurement problem as well as the EPR paradox. It does not introduce new equations to the formalism only a refinement of the interpretations of the relevant elements. The cost of this is that it establishes a quantum logic that contradicts classical logical, e.g. certain properties of a system can be both true and false, i.e. an eigenstate can have probability 0 and 1. These different probabilities occur in different framework, each valid, but in the formalism one can only apply one frame of work, though one is free to choose this frame of work. This, then, means that in consistent histories one has to abandon the notion of a physical reality where certain propositions are true regardless of what frame of work one has. There is no one true universe at any given time according to consistent histories [35].

4 Modal Interpretations

Modal interpretations are a group of interpretations which hypothesizes that besides the dynamical state, the wave function, a system also possesses a value state. This value state makes the system have definite values of observables even when it is not being measured, thus, these interpretations disposes of the eigenvalue-eigenstate link from the conventional formalism of quantum mechanics. However, the value state does ascribe definite values for a set of commuting observables at the same time. It is not possible to ascribe values of non-commuting observables at the same time through the value state. Modal interpretations are thus non-collapse interpretations where measurements are mere interactions, and not elevated to special treatment. What values can be ascribed to a system through the value state is determined by the actualization rule. This rule is what distinguishes the various modal interpretations from one another. An example of a modal interpretations is simply bohmian mechanics, where the value state corresponds to the particle's exact position. Another example is one proposed by Jeffrey Bub and Rob Clifton, where a privileged observable R is introduced. The observable R is privileged in the sense that it is always defined by the value state [36].

5 Transactional Interpretations

The transactional interpretation is one that centers on the results of the experiments concerning Bell's inequality, to prove that action-at-a-distance is an element of physical reality. Thus any interpretation of quantum mechanics must try and explain this nonlocality. The transactional asserts reality to the wave function ψ in the form of it being a retarded wave emitted forwards in time from an interaction, as well as the complex conjugated wave function ψ^* being a advanced wave emitted backward in time from an interaction[1]. The symmetry of time is thus very explicit in the transactional interpretation. The nonlocality of quantum mechanics is thus explained through the future influencing the past. The transactional interpretation is a collapse-interpretation, where the mechanism of collapse pertains to an event in the future, but it treats observation as a mere interaction, which further is constituted by a transaction of a retarded wave ψ and an advanced wave ψ^*, between the systems. System one emits the retarded wave ψ to system two, which then emits an advanced ψ^*, backwards in time to system 1 with amplitude $\psi\psi^*$. Thus, it is possible to derive the Born rule in the transactional interpretation. The transactional interpretation, does not add any mathematical structure, it only asserts a physical interpretation to the wave function and its complex conjugate [37] [38].

6 Statistical Ensemble

The statistical ensemble interpretation merely states that quantum mechanics is purely a statistical theory as statistical mechanics, and thus not a complete description of physical systems. The wave function in this interpretation then describes an ensemble of systems, not just one system, and there is in this way no need for a collapse of the wave function, since quantum mechanics only describes systems prepared, not observed. Furthermore it dissolves issues such as the measurement problem and the EPR paradox [39].

7 Quantum Information

Quantum information approaches vary, but they share the premise that the wave function describes information. Some theories describe this information in relation to immaterialism; physical reality merely consists of our knowledge of it, thus eradicating the distinction between epistemic and ontic. Not all approaches share this premise, there are approaches where the wave function only describes our knowledge of the system, and the collapse of the wave function describes our certainty of the observable in question during measurement. Qbism is a quantum information approach to quantum mechanics.

[1] Those familiar with Dirac's bra-ket formalism will notice that the bra space is put on equal footing as the ket space; both are equally real.

Chapter 9

Survey: Snapshot of Opinions Concerning Quantum Mechanics

A survey was carried out by creating a questionnaire concerning the foundations and interpretations of quantum mechanics. The questionnaire was greatly influenced by one carried out in 2013 by Schlosshauer et. Al. A large portion of the questions were taken from this survey, hereby allowing for a comparison between the answers gathered here and those of Schlosshauer et. Al.. The questions, as well as the answer-options, were attempted to be as a close to the original, in order to make a comparison. Some questions were changed though, because unlike Schlosshauer et Al. the questionnaire here was not solely meant for experts in quantum foundations, but were intended for all kinds of physicists, in order to give a representative picture of the attitudes and opinions of the physics community. Some questions and answer-options were reformulated, in the attempt to give an easy and clear message of what was meant with each element. At the end of the questionnaire, there was a comment box, where the participants could express or elaborate on their opinions about the subject. Before the survey was carried out, the questionnaire was tested on four physicists, who gave their opinion about the questions and the phrasing of the questions, in order to make the questions as clear as possible. However, in constructing a questionnaire with multiple choices not all opinions can be captured and some nuances will inevitably be lost. In the attempt of covering as many opinions as possible in the options, some options became very directed and extreme, as to capture one end of the spectrum. Some opinions might therefore not have been captured adequately by one of the options. A multiple choice approach was nonetheless taken, as it makes it possible to quantify the answers.

A personal link to the questionnaire was sent by email to 1234 physicists, who were either graduate-students, PhD-students, PhD-graduates, Professors or Lector Emeriti. Out of the 1234, only 150 participated in the survey, corresponding to about 12% answering the survey. One of these participants did not answer the online the survey, but wrote an email with his opinions and answers, so there are results from 149 of the participants.

The recipients of the email were chosen from their affiliation to various universities. 8 universities were chosen; Aarhus University, Copenhagen University, Göttingen University, Heidelberg University, Oxford University, California Institute of Technology, National University Singapore and University College London. The choice of the universities was mostly random, though certain factors did influence the choice. One factor was their connection to Aarhus University, since it was thought that more people would participate in the survey if it came from a university they knew well. Another factor was whether the university had a relation to the development of quantum mechanics, which would perhaps make people more inclined to answer from a sense of heritage. The choices of universities were also loosely based on the hope of getting a wide demographic. A last factor was simply a case of logistics; how easy or difficult it was to harvest the email addresses from the various universities' websites.

Other surveys of this nature, besides Scholsshauer et Al., have been carried out with varied results [40] [41] [42]. The survey here has significantly more participants than any of those referred to, and since it is distributed worldwide, it should give a more representative view of the opinions of physicists. The participants consist largely of Danes with about 44% of participants having Danish nationality.

1 Assumptions Before the Survey

Before the survey was carried out some thoughts were proposed. First of all it was believed that the Copenhagen interpretation would still be the dominating interpretation, not necessarily by a conscious choice, but simply due to the fact that it is the de facto interpretation. It seems that quantum foundations are not a subject which students are given an insight too, whether it be through courses concerning the topic or courses on quantum mechanics. Rather, the focus of most quantum mechanics courses is the application of the formalism, a "shut-up and calculate" approach to quantum mechanics. This hypothesis will be tested through questions that specifically ask what the participant associates with certain quantum mechanical concepts that touch upon the foundations of the theory. Secondly it was expected that there would be an inclination in Denmark towards the Copenhagen interpretation simply out of patriotism, both in regards to the name of the interpretation and the role Niels Bohr played in outlining it. Lastly, there was also an expectation that most would not have a great deal of knowledge concerning other interpretations than the Copenhagen interpretation.

Though the survey was sent out almost at random around the world, some considerations should be taken as to who answers these types of surveys. It is argued that people who have a vested interest and strong opinions on the matter would answer, and since the survey was sent out to this author's university as well, people who know the author would be more inclined to participate in the survey. Out of sample size of 149, these factors might skew the representation.

2 The Questions and What Was Answered

Question 1

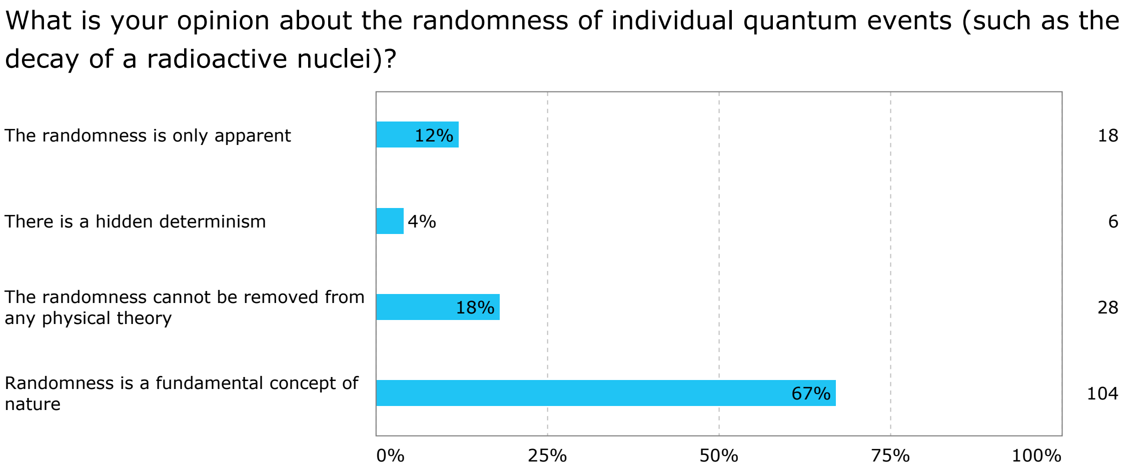

Figure 3: Distribution of all the participants' answers to question 1

The first question is intended to investigate the specific opinions regarding the randomness found in quantum mechanics, and was taken from the survey conducted by Schlosshauer et Al. The specific wording of this questions drew some objections during the testing-phase of the questions. The objections concerned the use of the word "opinion", since it was regarded that the word did not belong in physics, physics deals with facts. Rephrasing the questions as "*How do you understand...*" was suggested, but in the end ignored. First of all in order to compare the results here with Schlosshauer et Al. and second of all because it was felt that the different answers here are exactly opinions, and the use of the word understanding might lead uninitiated physicist to believe that there is a right answer and that they were being tested in their knowledge regarding the subject. The word opinion was, therefore, used as to remove the sense of one being examined in the knowledge of quantum mechanics. The various answers correspond to how one would answer the question from the viewpoint of different interpretations. Thus, the first option "*The randomness is only apparent*" corresponds to the answer one would give from the viewpoint of the many worlds interpretation, since the universal wave function evolves in a deterministic (non-random) way through the wave equation, but an observer is embedded in the universe moving along different branches giving rise to an apparent randomness seen by the observer. The second option corresponds to the answer one would give from the viewpoint of bohmian mechanics, where the observed randomness of quantum systems is only due to a lack of knowledge of the exact initial conditions.

Both the fourth and the third option can correspond to the Copenhagen interpretation, because of its vague definition. Heisenberg argued that the randomness in quantum mechanics, stems from "deficient knowledge" [9, chapter 3]. Bohr, however, sees this indeterminacy to arise from the concept of complementarity and the quantum postulate, which he regarded as describing nature. The fourth option also gives the view of the quantum fundamentalist, i.e. one who believes quantum mechanics is an ontological theory, and that the wave function describes an entity in physical reality. This was not the view of

Bohr, though [43], he held that the wave function was not a real physical entity.

The answers to this questions are shown in figure 3. It shows a significant majority of the participants preferring the fourth option, an opinion indicating a support for the views of Bohr in relation to the concept of complementarity. It could also imply a general view of quantum fundamentalism, and that a stochastic collapse process is real, though as of yet very ill described. Indeed, such a view might be expected of physicists not concerned with foundational issues relating to quantum mechanics. The insights into physics that a student gathers before meeting quantum mechanics, mostly relate to classical physics, an ontological theory which lends itself easy to interpret through daily experiences. In classical physics there are no reasons to worry about interpretation. If this has always been the case for a student, then when meeting quantum mechanics it would seem quite natural to use the same kind of interpretation, unless one's professor presents the concerns of the foundations.

It is rather striking how few have chosen option three, corresponding to the viewpoint of the Copenhagen interpretation in terms of Heisenberg.

A minority of the participants have chosen option one or two, but the results are nonetheless higher than what was found by Schlosshauer et Al. The overall low frequency does already indicate that the many-worlds interpretation and bohmian mechanics, do not find much favor among physicists.

Question 2

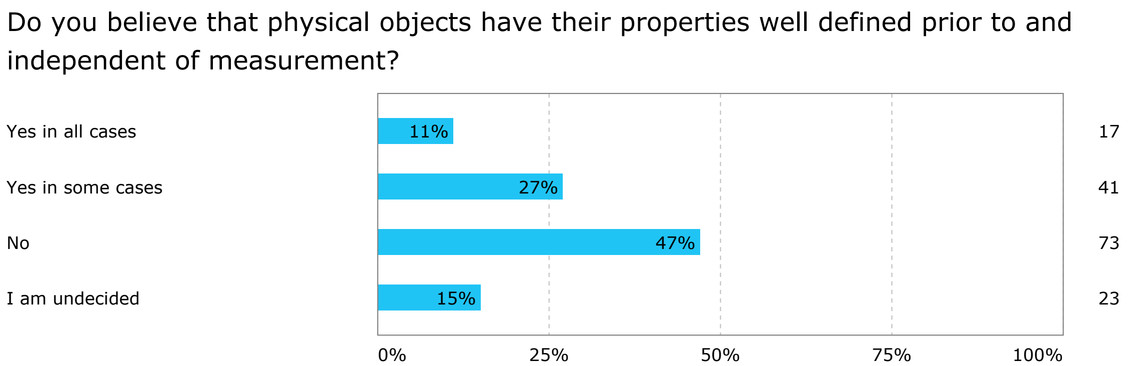

Figure 4: Distribution of all the participants' answers to question 2

The second question pertains to the role of measurement in defining physical properties and was taken from Schlosshauer et Al. This questions has some ambiguity to it, because it might not be well-defined, what is meant with the word "*physical property*". Indeed some participants sent an email regarding this exact ambiguity, highlighting that physical properties might be interpreted as observables or simply as the wave function itself. Another left the following comment regarding the question

"The second question is maybe not formulated that well. I would say that a quantum state is a well defined property of a system, but the system can still have a measurable quantity that does not have a well defined definite value. Both of these can be understood as properties of the system, but that is maybe the point of the question."

The question was selected with the intention that physical properties meant physical observables, such as energy, impulse, spin etc. The confusion stems from the fact that some see the wave function as specifying all elements of the system; there is only the wave function. This would be another sign of the prevalence of quantum fundamentalism. An approach of regarding the wave function as the only thing, is one taken in many text-books, but it feels more appropriate in the many worlds interpretation. The many worlds interpretation does not assume anything else than the wave function. In the Copenhagen interpretation, the wave function is not regarded as a real entity, so by claiming that there is only a wave function and nothing else, one is saying that there is nothing.

Bohr said the following in his Como lectures [13, p 368]

... radiation in free space as well as isolated material particles are abstractions, their properties on the quantum theory being observable and definable only through their interaction with other systems.

So Bohr uses the word "property" as intended by the question. This of course is semantics, and the use of the word by one physicist does not provide a guide of how the words should be used in relation to quantum mechanics[1]. The question was not altered since no objections were raised during the testing phase.

The intention of the question was to ascertain the participants' view of wave function collapse; is it a description of nature or our knowledge of a system? A more formal version of "Is the moon there when you are not looking?"[2]. The first option corresponds to what one would answer from the viewpoint of bohmian mechanics. In bohmian mechanics a state is described by a wave function in a superposition of eigenstates, corresponding to the particle being located in one of these eigenstates, but our lack of knowledge regarding the initial conditions, makes it impossible to infer which. The first could also be taken to represent the view of the Copenhagen interpretation, if one takes the approach advocated by Heisenberg. The second option could also represent another version of the Copenhagen interpretation, namely where the applicability of quantum mechanics is limited to the microscopic realm, and classical mechanics govern the macroscopic realm. This was indeed advocated by Bohr. The third option represents the many worlds interpretation, since physical properties only become well-defined when a measurement is performed. When this happens a splitting of the worlds occur, leaving the system of interest in a determinate state of the observable in question, so the physical property becomes well-defined. However, this option could also represent the views of yet another version of the Copenhagen interpretation, namely that of quantum fundamentalism, since properties only become well-defined after the collapse process has occurred, which is instigated by measurement. This question then illustrates, how the ambiguity of the Copenhagen interpretation, makes it encompass a variety of properties. The final option was simply to those who have are still undecided, and could represent those who have no favored interpretation.

The results show a clear majority in option three. The percentage of option three agrees very well with what was found by Schlosshauer et Al. However, they found that almost everyone else had chosen option 2, highlighting the limits of applicability of quantum mechanics. Here a little over a fourth chose this option. The number of people who chose the first option is significantly larger here, than in Schlosshauer et Al. indicating more adhering to Heisenberg's view. It could also be thought to indicate a support of bohmian

[1]Although Bohr certainly has been used in this manner, because of his unofficial status as the father of quantum mechanics.

[2]Allegedly Einstein posed this question in objection to the notion of collapse upon observation [6]

mechanics.

Question 3

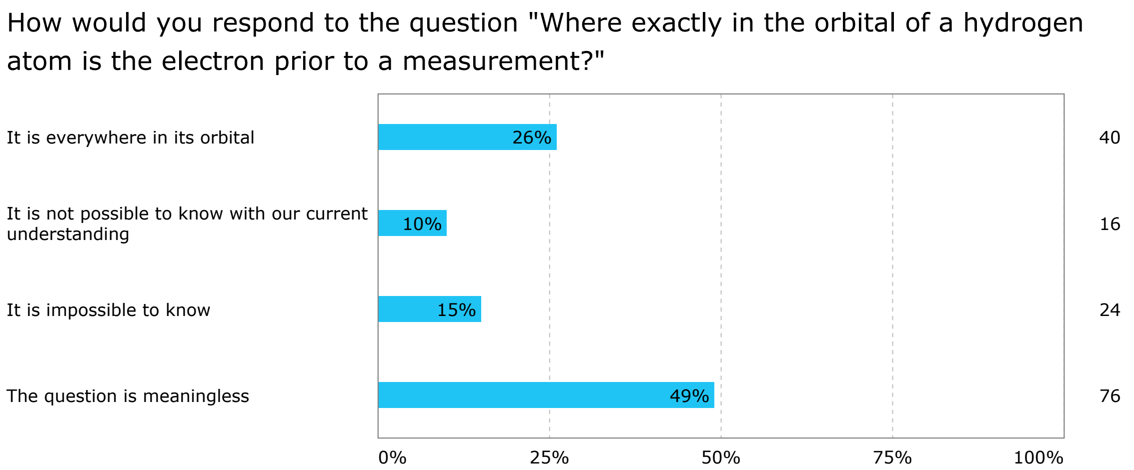

Figure 5: Distribution of all the participants' answers to question 3

The third question can be seen as a specific case of question 2, with the physical property being the position. The first option of the answers reflects a belief that the wave function is an ontic description of the system, representing the view of bohmian opinion, since the movement of the electron would be very rapid and violent according to bohmian mechanics. It could also be taken to represent a view where the probability distribution of the electron is taken as the position, although this does not fit any of the proposed interpretations. The second option has a subtle implication that it might one day be possible to specify the position. It is for those who believe that the electron does have a well-defined position, but quantum mechanics cannot provide the answer to this question. The option can be seen as representing the statistical ensemble interpretation, where quantum mechanics is regarded as a statistical theory along the line of statistical mechanics. The third option covers the view of the Copenhagen interpretation of Heisenberg, and the fourth option covers the views of Bohr's Copenhagen interpretation, as well as the quantum fundamentalism and the many worlds interpretation, since the position is not well-defined prior to measurement or interaction.

About half of the participants chose the last option meaning that there is a majority who considers the position ill-defined prior to measurement, which seems to conform to what was found in the previous question. Almost a fourth has the view of Heisenberg's Copenhagen interpretation and more than a fourth takes the view of bohmian mechanics, which at first seems rather strange, when comparing to the previous questions. It could also be that a number of the participants take the wave function's probability distribution to equal its position. This still does not make much sense, since it does not fit with any of the interpretations. It would represent a new kind of quantum fundamentalism, and another way of interpreting a superposition than merely stating that it is ill-defined.

Question 4

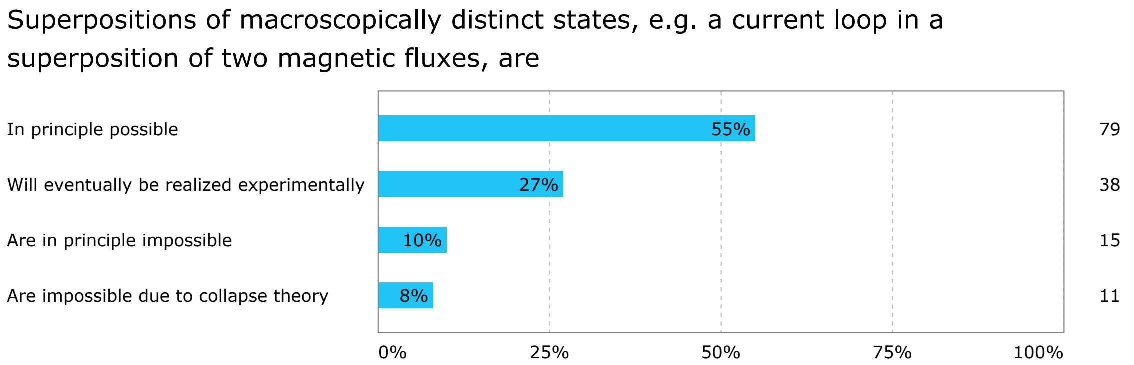

Figure 6: Distribution of all the participants' answers to question 4

The fourth question concerns quantum effects in macroscopic objects and is taken from Schlosshauer et Al. A small example of what is meant was added to the question in the hope of making the question clearer. It can be thought of as a version of Schrödinger's cat experiment, but without metaphysical states such as dead and alive. The question investigates the opinions surrounding the applicability of quantum mechanics. Experiments continue to demonstrate quantum behavior in bigger and bigger objects. The first option reflects the opinion that quantum mechanics is in principle applicable even at macroscopic scale. This viewpoint is consistent with most interpretations and quantum fundamentalism, but contrasts one of the Copenhagen interpretation, which sees the applicability of quantum mechanics and classical mechanics as separate. The second option says that not only is quantum mechanics applicable on a macroscopic scale, technology will eventually realize these effects on a macroscopic scale. The third option relates to those who see superposition as a mere concept of the mathematical formalism and not as something that belongs in the physical world. At first glance it might seem to appeal to bohmian mechanics, since particles are never in a superposition, but the quantum potential in bohmian mechanics gives rise to chaotic behavior of particles. Thus. it will cause the particles to move in such a way as to "mimic" a superposition. The third option is more in accordance with classical physics. The last option states that it is not possible, because the system would collapse.

The results show that a majority consider a superposition of macroscopic distinct states possible in principle, but will commit to them being realized technologically. The distinction between classical and macroscopic plays a central role in this question, since superpositions of classical distinct states are not observed. This majority represents the thought that quantum mechanics does not merely relate to our knowledge, but some parts of it do describe reality and not only on a microscopic scale. The concepts of classical physics, seem abandoned by most participants. The results found here agree with those found by Schlosshauer et Al, though a bigger percentage of their participants believe that these superpositions will be realized experimentally.

Question 5

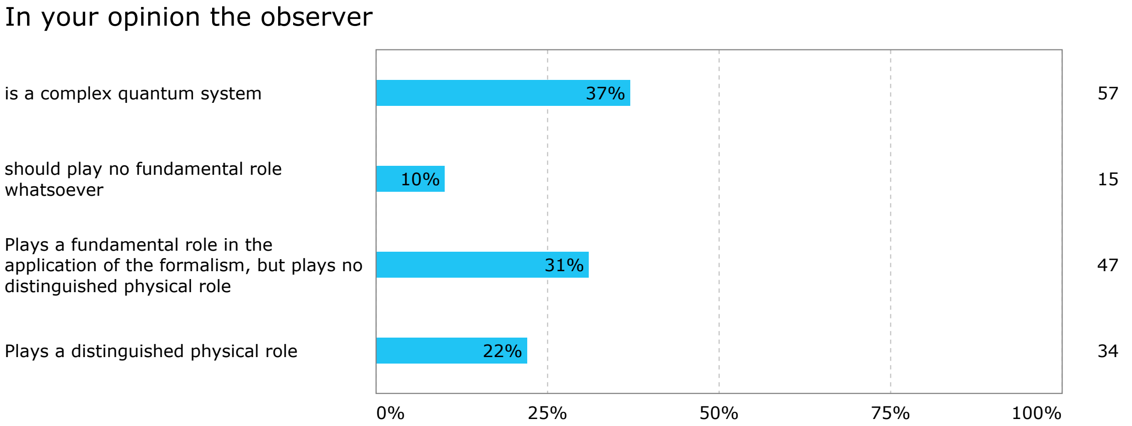

Figure 7: Distribution of all the participants answers to question 5

The fifth question concerns the role the observer plays in nature and is taken from Schlosshauer et Al. The role of the observer in quantum mechanics is different in the various interpretations. In the Copenhagen interpretation the observer plays a central role in establishing the properties of the system, and the observer is not described by quantum mechanics, the observer is external to the system, since he or she is described by classical mechanics. The first option is that the observer should be treated as a complex quantum system, which is what is done in the many worlds interpretation, Bohmian mechanics and more. The second option corresponds to the view of classical physics, where the observer plays no distinguished role whatsoever. One could reasonably argue that there is some overlap between the first and second option. The third option corresponds to the view of the Copenhagen interpretation when taken as a complete epistemic interpretation, where the observer is only important in the application of the formalism. The last option, then, reflects the opinion of those who consider the formalism as an ontic description, namely quantum fundamentalism.

The participants' answers were somewhat divided in this question. More than a third of the participants feel that the observer should be perceived as a complex quantum system, as is done in the many-worlds interpretation and bohmian mechanics. A little under the third of the participants feel that the observer plays a distinguished role in the application of the formalism, but no physical role, thus lending to an epistemic interpretation of the observer's role. And only 10% feel that the observer should play no role whatsoever as in classical physics. The distributions found here agree very well, for the two first options, with the results found by Schlosshauer et Al. However, it seems that a significant amount of the participants in our survey have preferred, the notion that the observer plays a distinguished physical role over the notion that the observer only plays a distinguished role in the application of the formalism. It should be highlighted here that the Schlosshauer et Al. had added a small remark to the last option "e.g., wave function collapse by consciousness", which was not in our survey. It was omitted so the option was not automatically related to consciousness, which would maybe deter some. Indeed this seems vindicated when comparing the results with Schlosshauer et Al.. As in Schlosshauer et Al. it is worth noting that more than 60% do not see the observer as a complex quantum system, which concerns the range of applicability of quantum mechanics.

The answers found to this question seem to go against the tendency established from the other questions, which have either showed a majority choosing the answer of the Copenhagen interpretations. This can, therefore, be seen as an element that most physicist are not satisfied with in standard quantum mechanics. One could also conjecture that it might be an indication that many physicist are not aware of the elevated status that the observer plays in standard quantum mechanics.

Question 6

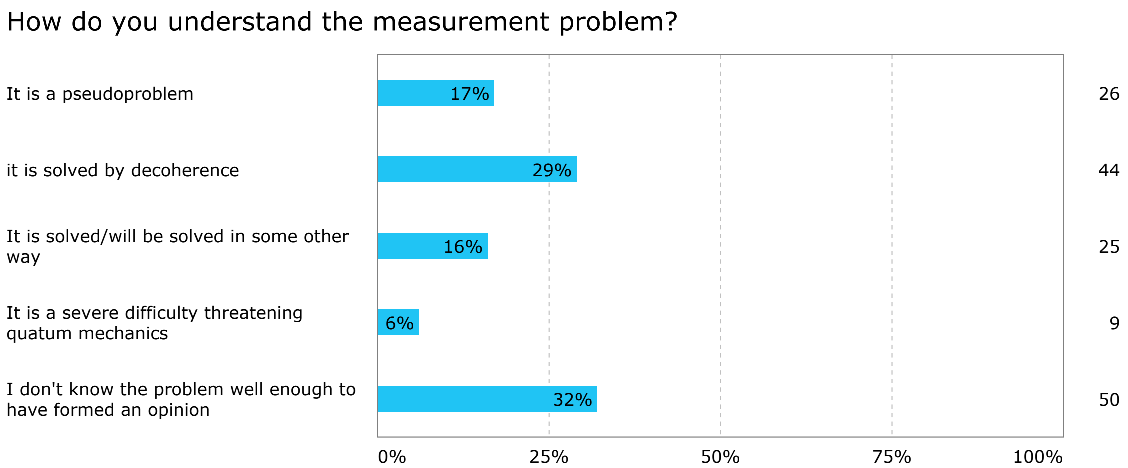

Figure 8: Distribution of all the participants' answers to question 6

The sixth questions concerns the measurement problem and is taken from Schlosshauer et Al. The measurement problem is often portrayed as "the" problem of the Copenhagen interpretations. The participants' answers will give an insight to whether it is perceived as being that by physicists. The first option reflects the viewpoint that quantum mechanics works, it gives the right predictions and since the measurement problem does not pertain to the application of quantum mechanics, it is not a problem. It also agrees with the viewpoint of the Copenhagen interpretation, when the wave function describes our knowledge of the system, and thus explains the collapse of the wave function upon measurement. The second option concerns the relatively recent developments regarding the transition between the quantum and the classical realm through decoherence. Decoherence solves some issues concerning measurement, namely the problem of preferred basis as has been seen. It does not solve the measurement problem, so here is one the few questions where there is a wrong option.

The third option corresponds to the viewpoint of the many worlds interpretation, bohmian mechanics and more, since the collapse of the wave function is explained as merely a feature from the perspective of the observer and not as an ontic concept or it is induced through decoherence and the guidance equation. Objective collapse theories provide an explanation of the collapse by adding non-linear terms in the wave equation, that instigate the collapse, so in these interpretations the collapse is an ontic concept, but one described explicitly, and would also be represented in the third option. The fourth option relates to those who feel that none of the aforementioned solutions are satisfactory and the measurement problem is still a severe difficulty of quantum formalism. A fifth and last option was added to the options provided by Schlosshauer et Al. to those who are not familiar with the measurement problem. This option felt necessary because unlike Schlosshauer et Al. this survey is not exclusively directed to physicists who deal with quantum foundations and interpretations.

The results here a very striking; first of all the results are very different from the ones found by Schlosshauer et Al., secondly, the majority of the participants are not familiar with the measurement problem. This gives an indication of what role foundations of quantum mechanics play in the mind of physicist; not a significant one. This, then, lends credence to the prevalence of the "shut-up and calculate" attitude which was expected as mentioned. Even more, of those familiar with the problem, it is a minority who view it as difficulty of the formalism, 6% of all the participants which is significantly fewer than the 24% found by Schlosshauer et Al. Furthermore 29% believe that is solved by decoherence which it is not, further emphasizing the apparent lack of knowledge concerning foundational issues.

Question 7

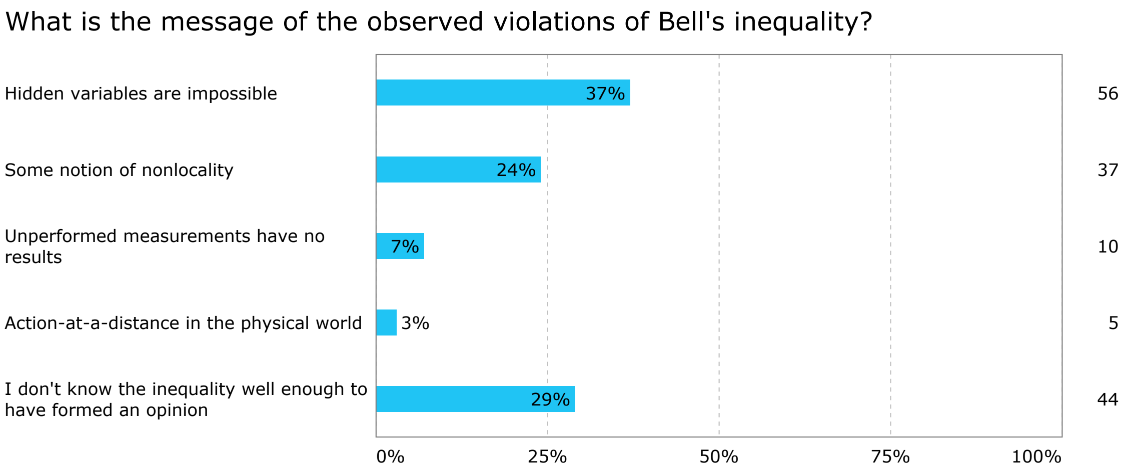

Figure 9: Distribution of all the participants' answers to question 7

The seventh question concerns Bell's inequality and its implication, and was taken from Schlosshaur et Al. Some of the answer-options were altered, since some of the concepts used in their answer options might be somewhat unclear for those not familiar with metaphysical terms relating to physical theories. The first option of the answers relates to those who are of the opinion that Bell's inequality concerns hidden variables, and how these are deemed impossible by the inequality. However, it is worth recalling that Bell's inequality assumes locality in its derivation, therefore nonlocal hidden variables are possible. Again, it is an example of one of the few wrong answer-options in the survey. It was altered to see if the participants knew of the underlying assumptions of the inequality. The second option is for those who feel that the message of Bell's inequality is concerning locality and that the violations imply that there elements of nonlocality, however, not necessarily in our physical world. This view agrees with the Copenhagen interpretation in Bohr's view where the nonlocality is not a sign of a mechanical force, but of an influence. The view also agrees with the many worlds interpretation, where nonlocality is only a feature of the splitting worlds, and locality is retained in each world. The third option reflects the opinion that because Bell's inequality shows that instantaneous collapse of the wave function of an entangled state at various locations is real, the system does not have well-defined observables, when measurements are not performed. It reflects the views of one of the Copenhagen interpretations. The fourth option relates to those who feel the greatest message of Bell's inequality is that nonlocality is real, thus dismissing the notion that the nonlocalities can be of an ephemeral nature. This entails bohmian mechanics as well as quantum fundamentalism. A last option of declaring an unfamiliarity to the subject of the question was again added since the survey is not targeted experts in quantum foundations and interpretations.

Once again the results show that a significant part of the participants do not know of a concept pertaining to the foundations of quantum mechanics. The majority understands the violations of Bell's inequality as excluding the possibility of hidden variables, which is not true, it only excludes the possibility of local hidden variables. Furthermore, 29% of the participants do not know the inequality, which means that two thirds of the participants do not have a proper knowledge of Bell's inequality. The answers again reveal ignorance concerning the foundations of quantum mechanics. It can also be thought to show a prevalence of a pragmatic approach to quantum mechanics, where the focus is on the theory providing the right predictions. The results highlight one of the problems that bohmian mechanics faces in gaining popularity. A lot of physicist might think that a hidden-variables approach is not tenable because of Bell's inequality.

Question 8

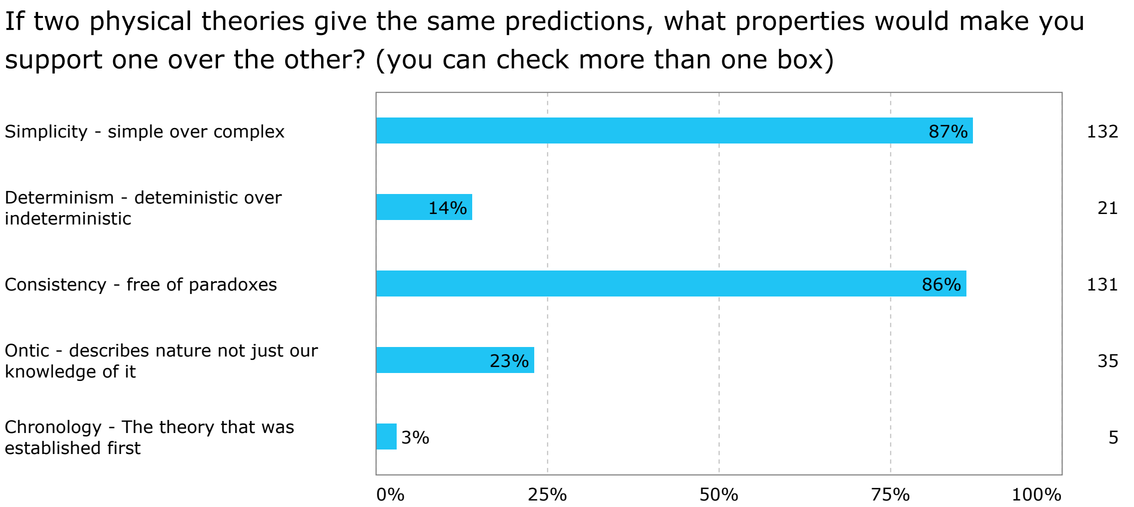

Figure 10: Distribution of all the participants answers' to question 8

The eighth question concerns what makes a good physical theory, specifically what makes one theory superior to another? This question does not only pertain to quantum mechanics, but to physics in general. Usually physicists rely on experiments to choose between theories, which implies that for a new theory to supersede the established theory it must make predictions that differ from the established theory. This was expressed by some of the comments from the participants.

Interpretations of a quantum mechanics is a useless waste of time. Since validity of the interpretation can not be verified experimentally, this line of research does not belong to physics.

If a new theory has several superior features, such as simplicity and consistency, compared to the established theory without any drawbacks, it will not supersede it if it makes the same predictions as the established theory. So the established theory might not be the best theory, but just the first one. Indeed it is worth contemplating what would have happened if De Broglie had not so easily abandoned his double solution theory after the fifth Solvay conference. Perhaps it would be the established theory today and our view on quantum mechanics would be very different from the one we have today. This is not to advocate that theories should be replaced as soon as a seemingly superior theory has been formulated, because a constant replacement of dominant theories would make it very difficult to teach the prevalent ideas to new students. However, to cling to experimental corroboration of new emergent theories is to elevate the established theory. The choice of the established theory, then, becomes of even greater importance, since it would be difficult, if not impossible, to let a more simple theory replace it. The question then is, whether this elevation of the established theory is too great? In this context it is also important to identify the properties which makes a theory superior to another if not experimental corroboration. When different theories give the same predictions, they are not considered distinct theories, but rather different interpretations. The question then asks what properties of an interpretation makes it superior to others. It was allowed that the participants could pick several options in this question. The first option is the same as Ockham's razor, the simplest explanation should be the preferred explanation. Answering the question of what simple is, of course carries an element of subjectivity. The second option relates to determinism and that it should be a desired property of a physical theory. The third option is consistency, claiming the important property of a theory to be consistent. The last option is simply chronology, whichever theory is chosen first. This option is the pragmatist's option, because in reality the reliance on experimental corroboration, makes the first theory the established theory.

The answers of the participants showed that a clear majority values the properties; simplicity and consistency. It is worth noting that so few have chosen properties as determinism and especially ontological. The answers show a divergence from the properties of classical theories. One cannot help but wonder if this divergence is a consequence of illumination, we are no longer confined to the properties that we once held in high esteem, or if it is signs of a dogma dragged down upon us, so that we glorify its properties and denounce the properties it lacks. Ockham's razor still plays a significant role in placing theories in relation to one another according to the results. If one regards simple as the fewest assumptions and fewest equation, then this leads to the many worlds interpretation. The many worlds interpretation solves the measurement problem by abandoning wave function collapse, gives a clear definition of an observer and does not distinguish between a classical and quantum regime, instead making quantum mechanics govern all scales. The interpretation is also an ontological interpretation which the majority might not find compelling, but 23% of participants do. It also lets the universal wave function evolve in a deterministic manner which is valued by 14%. However, at the face of it the many worlds interpretation seems anything but simple; worlds splitting into an infinite amount of worls, so to cover every possible outcome does not sound simple. One needs to examine the interpretation more thoroughly to understand its simplicity. When this is done it is realized that the stumbling block for the many worlds interpretation is the problem of implementing probability in the interpretation and deriving Born's rule, though there are suggested solutions to this problem. The Copenhagen interpretations assumes Born's rule, wave function collapse and the evolution of the wave function through the Schrödinger equation. One version limits its application to the atomic scale, even though larger scales consist of atoms. The question of whether it represents the simplest form of the argument is left open. Finally bohmian mechanics could be argued as being simple, since it only assumes two equations, one which has even been implied to be so evident that a student could guess it by a bohmian mechanics proponent[3], and is completely consistent. Furthermore, bohmian mechanics is an ontological interpretation and has an even more explicit deterministic nature than the many-worlds interpretation. However, bohmian has the explicit feature of nonlocality which could be argued to conflict with consistency and the notion of active information could be regarded as a further assumption, thus, making it less simple. The preference of the participants cannot be used to infer a clear logical choice of interpretation, since there still exists a great deal of subjectivity in applying these concepts. However, it is difficult to see the Copenhagen interpretation as the preferred interpretation, as the favored properties are not easily compatible with the interpretation and only 3% find it important what interpretation came first. The fact that only 3% choose chronology, is noteworthy considering the importance of experimental corroboration in the physics community, which naturally leads to an elevation of the first proposed theory.

Question 9

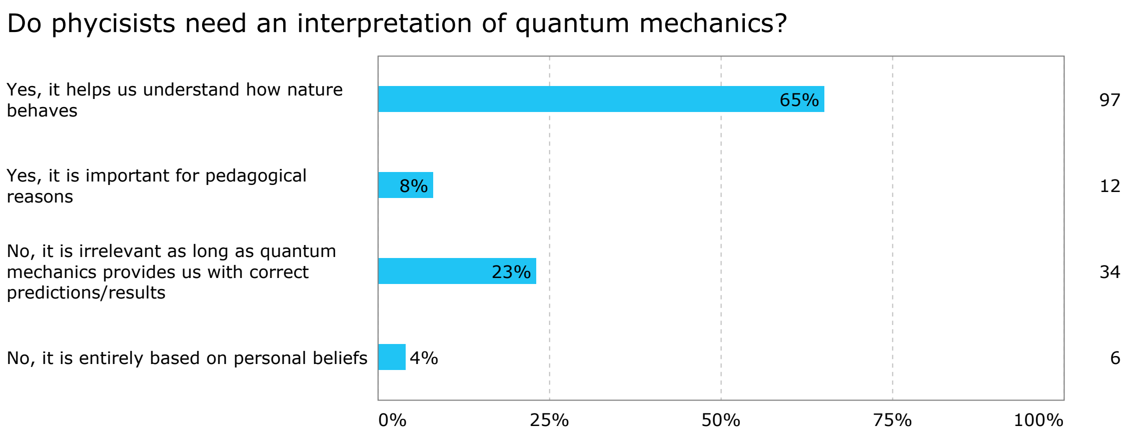

Figure 11: Distribution of all the participants' answers to question 9

The ninth question concerns the role a physical interpretation plays and whether it is something physicists needs. Beyond the various interpretations there is a pragmatic approach to quantum mechanics, the "shut-up and calculate" approach, where the thought is; as a long as quantum mechanics provide the correct predictions, one should not be concerned

[3]This was done by Sheldon Goldstein at the World Science Festival 2014: `https://www.youtube.com/watch?v=GdqC2bVLesQ`

about the interpretation and foundations of quantum mechanics. This questions seeks to investigate the prevalence of this approach as well. The first option reflects that physicists need an interpretation of the theory, since it relates the link between the mathematical formalism and nature. One could argue that this rules out epistemological interpretations, such as one version of the Copenhagen interpretation, since they only relate to our knowledge not nature as it is. Our knowledge and nature itself are not necessarily two distinct elements, indeed if one regards quantum mechanics as a purely epistemological theory, one still must concede that it does say something about nature as it is, given its predictive power. The second option is the opinion that interpretation serves a role when teaching quantum mechanics. An interpretation makes it possible to visualize certain aspects of a theory and enables one to apply the theory to a given situation. This opinion was expressed by a participant in the comments.

In my opinion, the interpretation is proposed to help us to understand quantum mechanics theory. As far as I can see, it does not prevent us from using the theory to understand the nature itself. There is no question about which interpretation is wrong or right. The only question is which interpretation can help us to understand the nature easily and most currently.

The third option represents the "shut-up and calculate" approach where quantum mechanics is merely regarded as a tool to give predictions. Some of the comments reflected this attitude.

Mostly I an am empiricist, in that as long as a theory predicts what we measure, I don't really care at all how it is interpreted. And it doesn't bother me if those predictions are only statistical in nature. But if pressured, I'll explain that Bell's shows us local hidden variables are incompatible with experiment, so hidden variables must be nonlocal, and nonlocal is quite distasteful. (Distasteful is obviously a subjective thing, not an experimental thing). So it seems that leaves us with many worlds – but I think it doesn't matter, unless you can find an experimental consequence. (That's actually what's so nifty about the history of Bell's– it's a physical consequence of local hidden variable theories, and the experiments therefore rule such theories out). So that means it's on people who care to show that there is an experimental consequence of the remaining interpretations.[4]

The fourth option relates to those who feel that the choice of interpretation is a personal choice, since all interpretations give the same predictions the properties one desires from nature, makes one decide which interpretation one chooses to believe in. This attitude was hinted at in the first quotation.

There is a clear majority who feel that interpretations are necessary since it helps us describe nature. This seems quite at odds with the fact that only a fourth value an ontological theory. It could indicate that not many physicist give much thought to the distinction of epistemology and ontology. A complete ontological theory would also give rise to an epistemic description, since all that is, is known. Vice versa a completely epistemic theory that always gives the right predictions cannot be completely detached from nature, this could explain the mixed emotions displayed by the participants. Furthermore it could be that not all are familiar with the epistemic nature of the Copenhagen interpretations.

[4]This comment also reflect some of the arguments put forth in the previous question.

Indeed Sheldon Goldstein expresses this in a debate regarding quantum foundations.

"*it's based on a mistake. A mistake that everybody took, almost all physicists somehow took for granted, that is taking the wave function as the only element of the reality, the only thing that is real for a quantum system is its wave function. As soon as you say you've got more than a wave function well then there is no need whatsoever for many-worlds and what I find striking is that this dogma that wave function is everything, even extends to, so many physicist who don't regard the wave function as real at all. Many physicists, it's far less than a majority of physicists that take the wave function seriously as something that's objective real, when they say, many physicist when they say "it is a probability wave" they really mean it just reflects our information, it is subjective not something really out there. Nonetheless many of those same physicist still say "there is nothing more than wave", which would seem to suggest that there is nothing*"[5] [48]

23% could almost be said to have chosen the "shut-up and calculate" approach by expressing that the interpretation of quantum mechanics is irrelevant as long as the predictions are correct. Only a small minority feel that interpretations are a matter of personal belief or important for pedagogical reasons. Thus, it seems that physicists emphasize a theory's ability to describe nature and to give correct predictions in that order.

Question 10

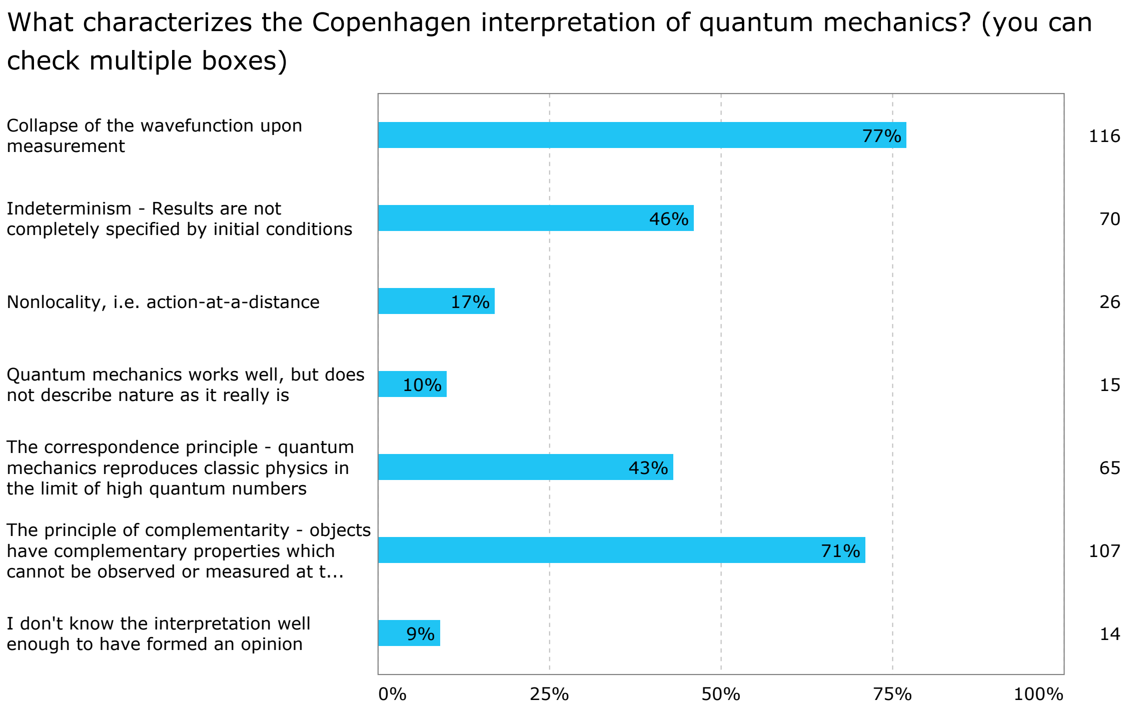

Figure 12: Distribution of all the participants' answers to question 10

The tenth question concerns the Copenhagen interpretation and intends to uncover what physicist associate with the Copenhagen interpretation. As highlighted earlier, the Copen-

[5] https://youtu.be/GdqC2bVLesQ?t=3516

hagen interpretation is not one well-defined interpretation, demonstrated by the fact that the founders of the interpretation have differing views. There are several concepts related to the Copenhagen interpretation[6], and it is the association with these concept that the question investigates. The participants were allowed to pick multiple options in this question. The first option is the concept of wave function collapse upon measurement. Other interpretations include wave function collapse as well, like objective collapse theories, but the collapse in the Copenhagen interpretation has no rigorous description, and is an additional assumption added to the interpretation. The second option is indeterminism, which was a significant break from classical physics when the interpretation came to the fore. The third option is nonlocality, though it is not an explicit property of theory, the Copenhagen interpretation does contain some notions of nonlocality. The fourth option relates to the epistemic nature of the Copenhagen interpretation, which again made it significantly different from classical physics at the time of conception. The fifth option is the correspondence principle and the sixth option is complementarity. The last option is again for those who feel unfamiliar with the Copenhagen interpretation.

The most striking element of the results is that very few of the participants associate epistemology with the interpretation, thus, in the majority's eye, the Copenhagen interpretation gives an actual account of nature's behavior, which is still different from what Bohr thought of quantum mechanics, though he had a more ontological approach to quantum mechanics than Heisenberg. It lends credence to the two hypotheses already discussed, namely the prevalence of quantum fundamentalism and a lack of distinction between ontology and epistemology. It could also indicate that many do not know of this property of the interpretation. The collapse hypothesis is what the majority of the participants associate with the Copenhagen interpretation closely followed by complementarity. The collapse hypothesis does play an important role in the application of quantum mechanics, since it specifies the link between measurements and wave function, acting as a tool for "shut-up and calculate" approach to ignore the measurement problem. However, the role of complementarity does not play a central role in the application of the formalism, but does so in its role to provide an understanding of the formalism. This then seems contradictory to the assessment that "shut-up and calculate" is the prevailing approach among physicist, who identify themselves as adhering to the Copenhagen interpretation. However, it is important to note that the question only concerns the association with the Copenhagen interpretation, not what concepts the individual participants view as important or indeed what these concepts entail. There are many examples of misunderstandings of complementarity, from what Bohr originally conceived it to be. The argument of nonlocality that Einstein, Podolsky and Rosen used to argue that quantum mechanics is incomplete, would not seem to deter the participants from the Copenhagen interpretation, since only a minority associate nonlocality with the interpretation. This again seems rather striking, since few associate the Copenhagen interpretation with an epistemological interpretation. This lends credence to the notion that many physicist do not have a proper understanding of what the Copenhagen interpretation is, though only 9% choose this option.

[6]The exact definition of these concepts are not unanimously agreed upon as mentioned earlier.

Question 11

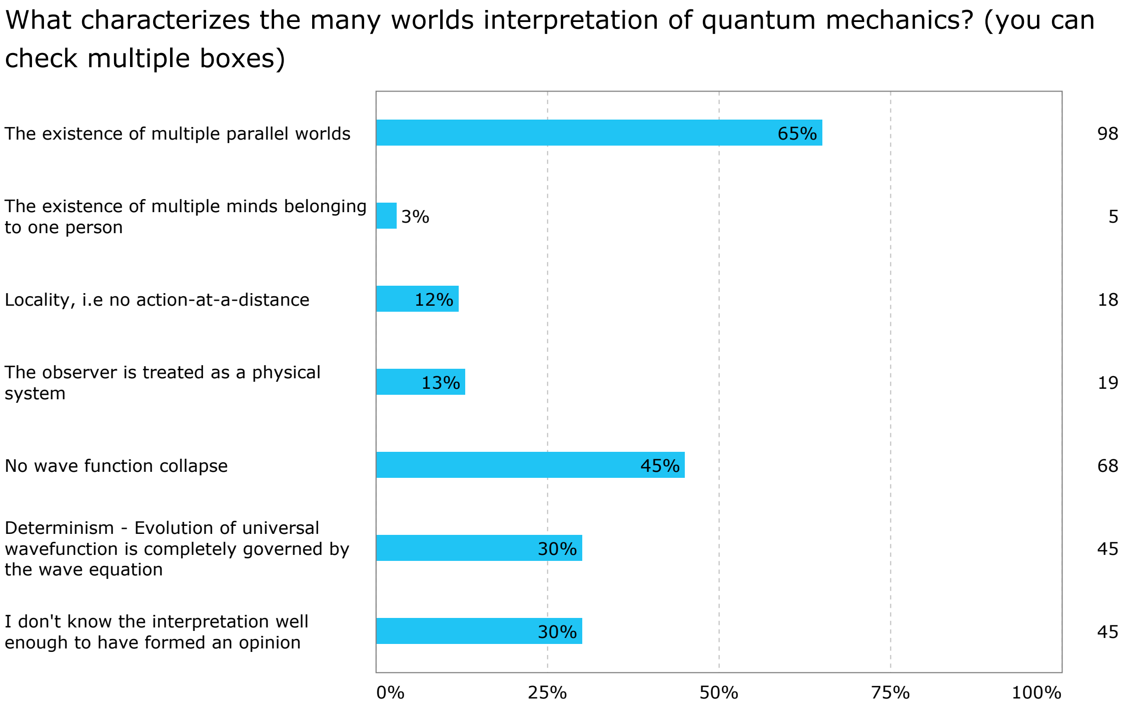

Figure 13: Distribution of all the participants' answers to question 11

The eleventh question concerns the many worlds interpretation and like the previous question intends to uncover what physicists associate with the interpretation. The many worlds interpretation contains several features, but not all are necessarily known by all physicists. As in the previous question, the participants were allowed to pick several options. The first option is the metaphysical concept of multiple worlds that the many worlds name refers to. The second option is the metaphysical concept of many-minds which can be employed instead of the many worlds. The two are in reality separate interpretations, but have been handled as the same here, because they share the same formalism. The third option is the retained property of locality in the many worlds interpretation, though this is not an obvious feature of it, since the splitting of worlds is not a local process. The fourth option relates to the fact that, unlike the Copenhagen interpretations, the observer is not assigned any elevated role and is thus just treated as a complex quantum system. The fifth option has some overlap with the previous option, since it is the absence of wave function collapse, which instead is viewed as a branching of the universal wave function. The sixth option is determinism which is recovered for the universal wave function, but a seemingly indeterminism remains from the view of the observer. The last option is once more for those who feel unfamiliar with the many worlds interpretation.

Here a clear answer is given, which is that the main association with the many worlds interpretation is the postulate of many worlds. This of course is not surprising, since the existence of multiple worlds is expressed in the interpretation's very name. Physicist do not seem familiar with other features of the interpretation, such as locality and the observer being treated as a quantum system. However, almost all of the participants associated no collapse to the theory, which is readily implied by the worlds corresponding to every possible event.

From the description of the many worlds interpretation it is recalled that what was central to Everett was to solve the measurement problem, and he never used the word "worlds" in his thesis. His focus was on rejecting the collapse postulate. De Witt popularized the interpretation, but maybe he actually did it a disservice. He may have made many people aware of the interpretation, but in popularizing the interpretation, by postulating an almost science fiction like process, he also may have prompted most physicist to deny it at first instance. The many worlds of the many worlds interpretation take the focus away from where many of its adherent place theirs. Where the Copenhagen interpretation can still find a central place for classical mechanics, in that the observer and the measurement apparatuses should be described by it, the many worlds interpretation can be seen as the ultimate "quantum mechanical interpretation" of quantum mechanics. Indeed this is what Everett himself referred to in his original thesis [21], where he named his theory *pure wave mechanics*.

Question 12

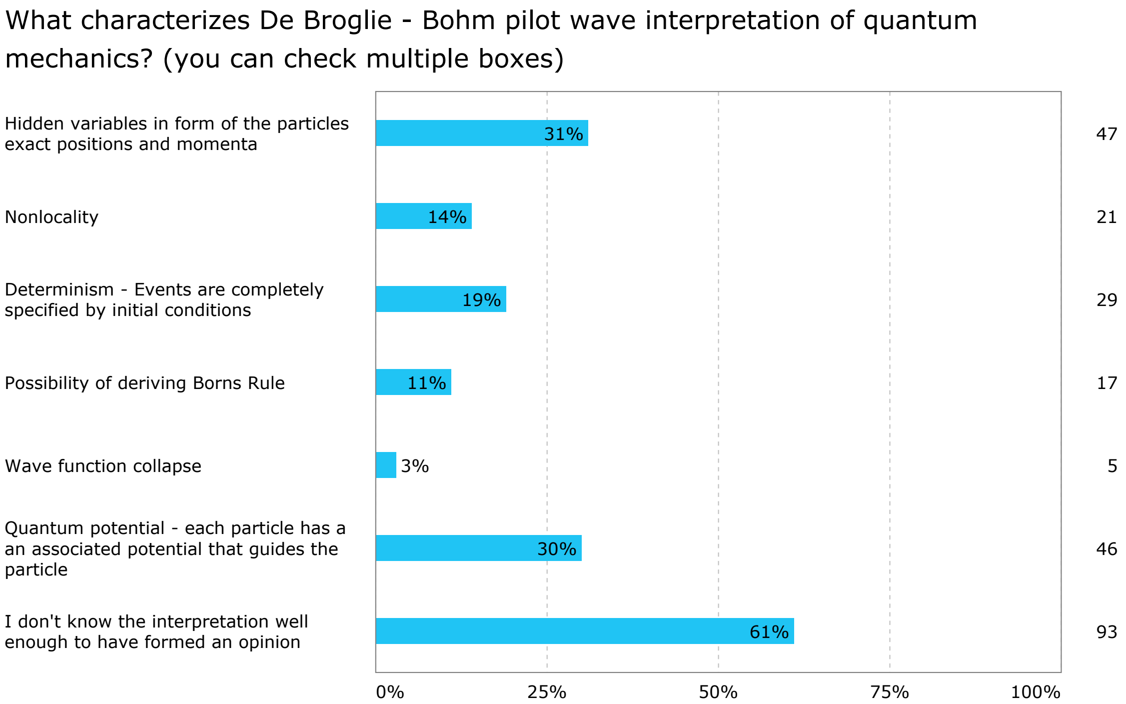

Figure 14: Distribution of all the participants' answers to question 12

The twelfth question concerns bohmian mechanics and like the two previous questions intends to uncover the associations made with the interpretation by physicist. Bohmian mechanics is probably the least known interpretation of the three focused on here, so not all features of the theory are expected to be known by physicist. The first option is the hidden variables of the interpretation. This feature would be thought to be the most distinguishing feature of the interpretation. The second option is the nonlocality which is made very explicit in bohmian mechanics, unlike in versions of the Copenhagen interpretation. The third option is determinism, which is made possible because of the hidden variables. The fourth option relates to the fact that one can derive Born's rule in the scheme of bohmian mechanics, which is not possible in the other interpretations given attention here. The fifth option is the apparent collapse of the wave function in bohmian mechanics, that is attributed the fact that the particle "hides" in only one of the eigenfunctions. The sixth option is the quantum potential that guides the particle through the guidance equation and whose evolution is governed by the wave equation. The last option is once again for those who are not familiar with bohmian mechanics.

More than half of the participants are not familiar with bohmian mechanics. This was expected as it does not have an ostentatious name as the many worlds interpretation and does not create the same attention around itself. Furthermore, as seen before, many believe that the message of Bell's inequality is that hidden variables are impossible, thus, deterring people away from hidden variable interpretations such as bohmian mechanics. Of those who know of bohmian mechanics[7]most associate the interpretation with hidden variable and the quantum potential. Very few associate it with the possibility of deriving Born's rule. This is noteworthy, since it is one of the few interpretations that has this feature, restricting itself to only two assumptions.

[7]A small percentage of those who chose the option that they did not know the interpretation, have marked other boxes as well. There were at most 3 participants who chose the same given option, who had also picked the last option.

Question 13

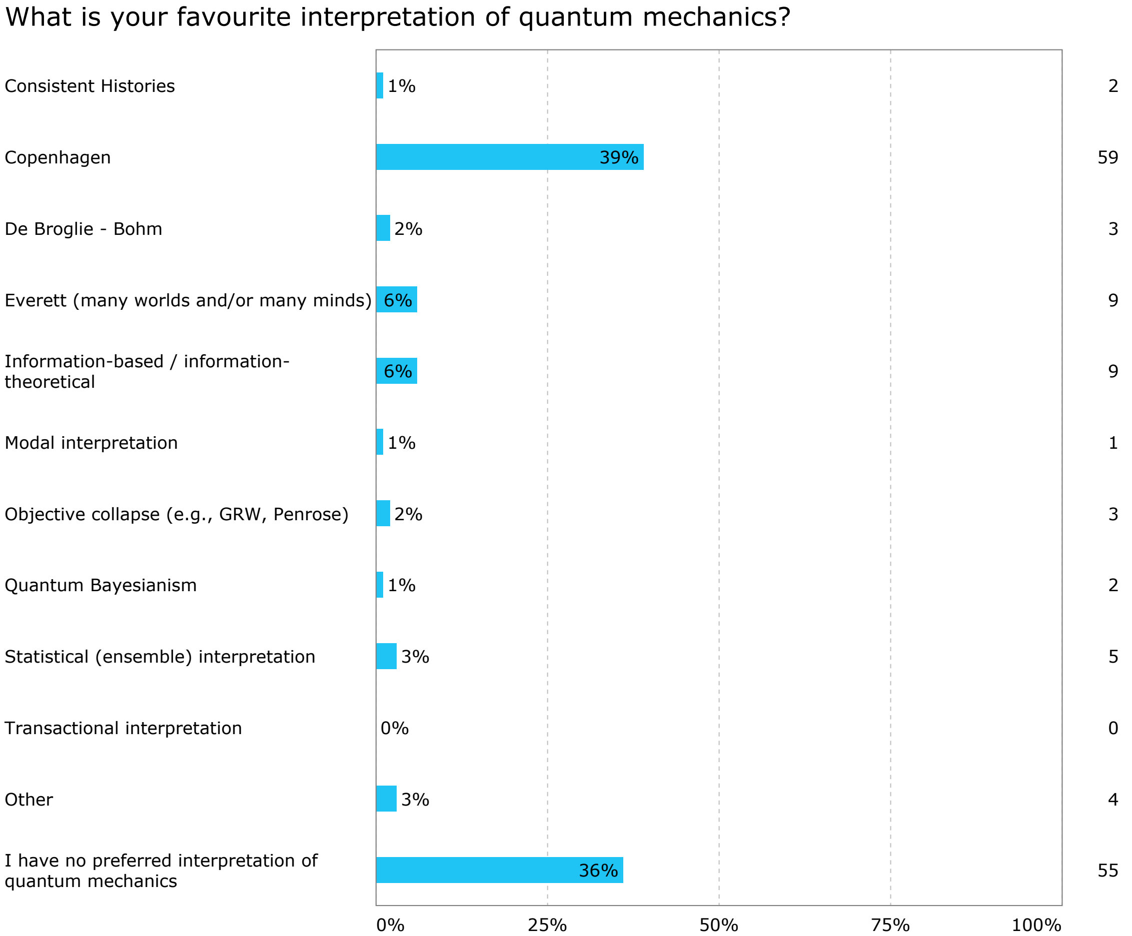

Figure 15: Distribution of all the participants' answers to question 13

The thirteenth question can be considered as the main question of the survey, since it concerns which interpretation is the most popular today. This question is also formulated by Schlosshauer et Al. The various options corresponds to the different interpretations presented here. Besides these options a last option of having no preferred interpretation of quantum mechanics is available to incorporate those who do not feel that there are any satisfactory interpretations of quantum mechanics, as well as those who have a "shut-up and calculate" approach to quantum mechanics.

The results here show that the Copenhagen interpretation is still by a large margin the preferred interpretation of quantum mechanics with 33 percentage points separating it from the many worlds interpretation and information theoretic approach, which has been said to be an offspring of the Copenhagen interpretation.

It seems as if there is a genuine sense that quantum foundations are moving forward in the physics community and that it is no longer considered career suicide to engage in this field [1]. However, the attitude and opinions of physicists seem as of yet unmoved with such a majority still citing the Copenhagen interpretation as their preferred interpretation, and with so few supporting alternative interpretations. The opinion of the physics community still hold the Copenhagen interpretation supreme, as was also found in Schlosshauer et Al. While they found that preferences of those who do not prefer the Copenhagen interpretation, were distributed fairly evenly between 5 other interpretations[8], the results here show that more than a third have no preferred interpretation, lending a lot of credence to the notion that most physicists have adopted a shut-up and calculate approach. It could also be taken as a sign that quantum foundations and interpretations are playing a bigger role today than before. Because some of the problems that are associated with standard quantum mechanics, physicist choose not to support the interpretation, but may not necessarily go looking for another interpretation as long as they can apply the formalism. Those who chose the last option also display a sense of awareness of what they believe, instead of, almost blindly taking to the Copenhagen interpretation. Furthermore, it also seems as the other interpretations have a severe disadvantage when compared to the Copenhagen interpretation, which is that they are well-defined. This might seem as an advantage, but because the Copenhagen interpretation is such a vague collection of various, and even contradicting, statements, then it seems that it has higher chance of conforming to varying attitudes towards quantum mechanics.

Question 14

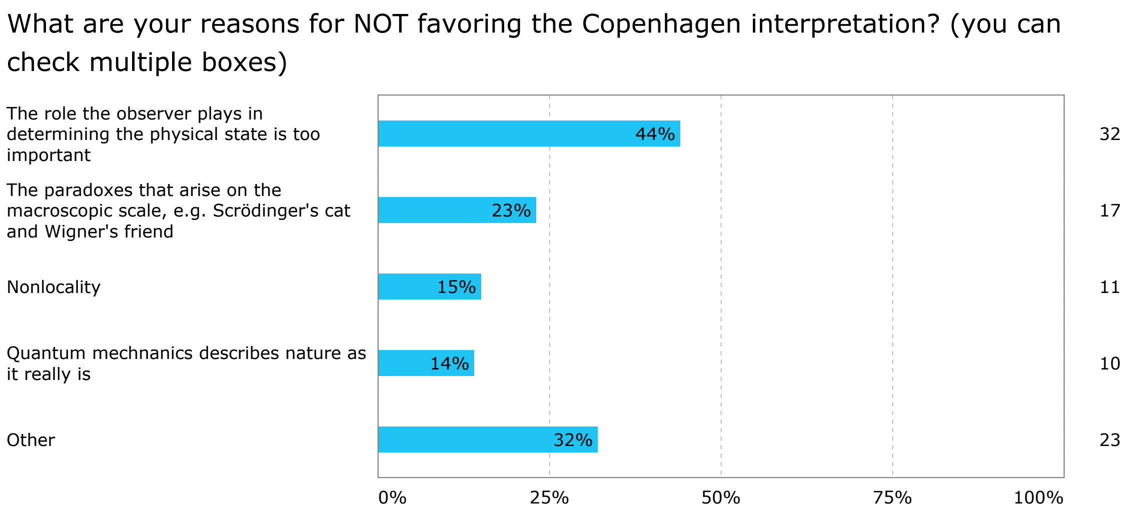

Figure 16: Distribution of all the participants' answers to question 14

The fourteenth question concerns the features of the Copenhagen interpretation that seem dissuading. The question was not displayed to every participant, but only those who had not chosen the second option in question 13, i.e. that they preferred interpretation of quantum mechanics is the Copenhagen interpretation, or the seventh option of question 10, i.e. an unfamiliarity with the Copenhagen interpretation. This filter was chosen since it did not seem to make much sense to pose this question to the participants who had chosen these options. The participants were allowed to pick multiple options to this question. The first option is the distinguished role the observer plays in attributing a system's physical properties. The second option is the various paradoxes that arise when quantum formalism

[8]They were distributed between the many worlds interpretation, information based interpretations, Qbism, and Objective collapse.

is applied to the macroscopic scale such as Schrödinger's cat or Wigner's friend. The third option pertains to the nonlocality of the interpretation highlighted by Einstein, Podolsky and Rosen in their famous article. The fourth option relates to the epistemological nature of the Copenhagen interpretation and suggests that physical theories should be ontological. The last option is simply other reasons than the ones listed here.

Of those who do not favor the Copenhagen interpretation, the majority states that it is because of the role the observer plays in the interpretation that they do not favor it.

A significant part of the participants chose "other", which could imply that a significant reason has been omitted as an option. It is thought that more complex reasons, that are not readily formulated as a survey option, are behind the high frequency of the last option. This is indeed corroborated by some of the comments left by those who chose the last option.

"A comment on the survey: The answers available for some questions were too limited to capture my view. Some of my views may be a matter of internal beliefs/taste, not out of comprehensive physical understanding."

"One big reason for my personal preference of many-worlds is the simplicity of this description: you avoid the wavefunciton collapse mechanism. so, this is kind of an ockham's razor argument. however, it is not clear to me why ockham's razor should be valid when interpreting QM - it is not a typical modeling situation! therefore i consider my personal preference towards many-worlds to be more-or-less a matter of taste, as i am incapable of arguing strongly for one or the other interpretation"

"I am all for the CPH interpretation but with a twist: The Bell theorem violation is not so bad once you realize that no information can travel faster than light. Correlations can, but they seem like noise until you communicate on a speed-of-light-limited channel to figure out that things were correlated. That's still pretty strange but at least it does not violate special relativity: Classical correlations can also "travel" faster than light (I have two marbles: one black and one white. I put each in a sealed bag and send one of the bags to the side of the galaxy. When I open the bag left behind, I instantly know the color of the marble even if lightyears away). So at the end: CPH interpretation + some informatino concepts in a not entirely consistent mixture"

"I could not really answer honestly several of your questions because no option covered my position. I consider Copenhagen a clever workaround of the impossible problem that arises once one recognises that all measurement is disturbance (see Binney & Skinner OUP 2013). It's obvious that much of the randomness derives from the unknown quantum state of measuring kit. The real issue is why it's ok to compute probabilities from complex amplitudes and I've never seen any intelligent discussion of this. I find the "foundations" literature sterile as a consequence. Moreover, to me it's evident that all discussion at the level of single-particle QM is futile: electrons don't exist as photons don't exist. These are just excitations of fields. Complementarity, de-localisation are trivial consequences. Nature will not be understood without engaging with QFT. Probably not even then since QFT is just an effective theory valid on scales larger than the unknown fundamental structure of the vacuum."

Question 15

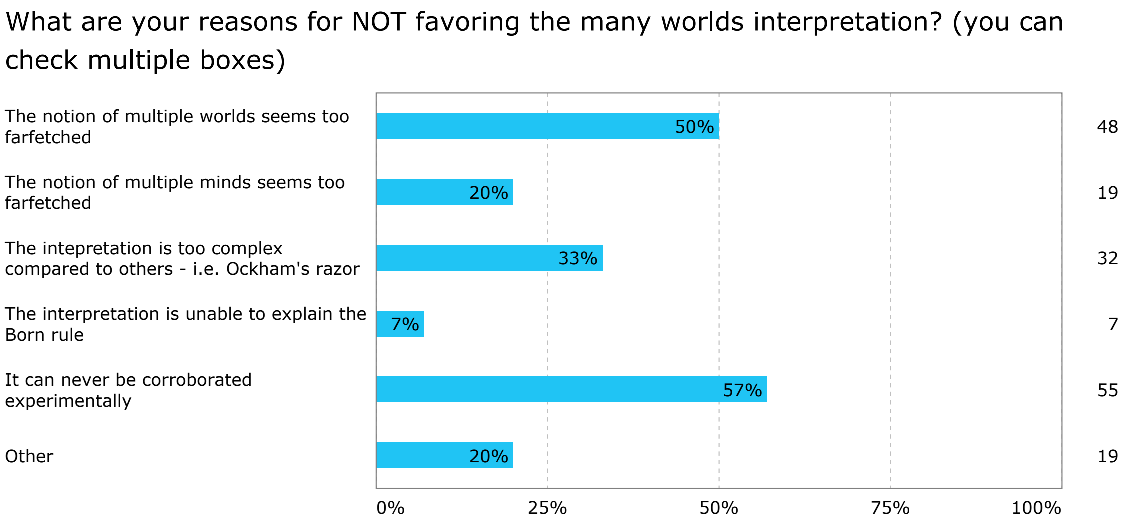

Figure 17: Distribution of all the participants' answers to question 15

The fifteenth question concerns which features of the many worlds interpretation seem dissuading. As the previous question, this question was not displayed to the participants who had chosen the fourth option in question 13, i.e. that they favor the many worlds interpretation, or the seventh option of question 11, i.e. an unfamiliarity with the many worlds interpretation. This filter was chosen out of the same reasons for the previous filter. The participants were allowed to pick multiple options to this question. The first option relates to the metaphysical assumption of multiple worlds, which can seem quite far-fetched. The second option is like the first option only concerning the assumption of many minds. The third option regards the complexity of the interpretation, which might at first seem larger than that of other interpretations, such as the Copenhagen interpretation. The fourth option relates to the difficulty of explaining probabilities in the many worlds scheme, specifically the inability to derive the Born rule in the interpretation. The fifth option is the problem of verifying the interpretation through experiments. This problem relates to a lot of the other interpretations, but few of the other interpretations contain grandiose statements, such as the existence of many worlds, where every possible outcome happens. The last option is other reasons than the ones listed here.

The results show that the notion of many worlds is what deters many from the interpretation. This is implied both in that half of the participants picking the option that multiple worlds seems far-fetched, as well as the fact that more than half of the participants do not support the interpretation, since it can never be corroborated experimentally. The need for experimental corroboration seems logical because the statement of many worlds is very bold. Every measurement produce distinct non-interacting worlds, which seem to contradict the possibility of ever being able to find experimental corroboration. However, the non-interacting aspect comes from decoherence, so in principle there is a finite amount of time where worlds can interact. This time interval is minuscule, of the order 10^{-14} [24], and it does not seem possible in any future to make experiments that could verify the interpretation [45]. Furthermore, one could argue that the need for experimental verification seems at odds with the fact it is the interpretation with fewest assumption. The

Copenhagen interpretation postulates collapse, so it would seem that collapse should be subjected to experimental investigation.

Again it has to be asked whether the biggest problem with the many worlds interpretation is its name. If instead of postulating multiple parallel worlds, one took the interpretation as Everett originally formulated it, as a homomorphism rather than an isomorphism, would the many worlds interpretation be more popular today under another name? This is of course all speculation, and it could be argued that the popularity of the many worlds interpretation stems from its ostentatious name, drawing a lot of attention to itself.

A third of the participants find the interpretation too complex, which implies that many do not know the interpretation sufficiently well. It is hard to find a definition of simple, where the many worlds interpretation is not viewed as the most simple, or at least as simple as the other interpretation. It has fewer assumptions than any of the other interpretations, the wave function does not collapse and the universal wave function evolves in a casual deterministic manner. Indeed as highlighted in the section concerning the many worlds interpretation, its biggest problem is in handling probabilities, but only 7% of the participants chose this option. This again leads to the conclusion that physicists are not that familiar with the interpretation, besides the metaphysical postulate of multiple worlds. This unfamiliarity seems to go beyond the 20% who declared it by choosing the seventh option in question 11.

Question 16

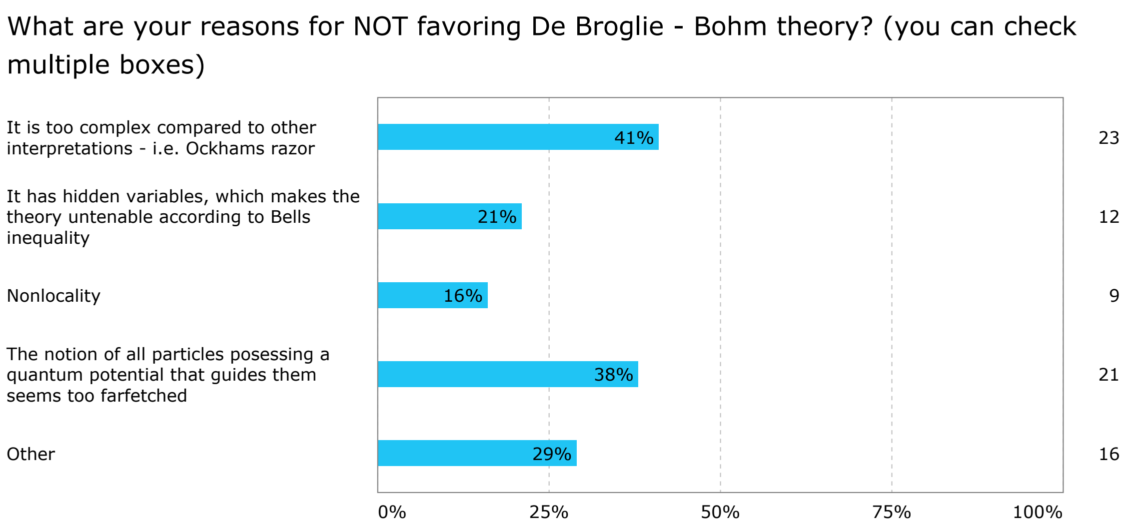

Figure 18: Distribution of all the participants' answers to question 16

The sixteenth question concerns what features of bohmian mechanics seem dissuading. As the two previous questions, this question was not displayed to the participants who had chosen the third option of question 13, i.e. that they favor bohmian mechanics, or the seventh option of question 12, i.e. an unfamiliarity with bohmian mechanics. This filter was chosen out of the same reasons as for the previous filters. The participants were allowed to pick multiple options to this question. The first option is Ockhams razor, implying that bohmian mechanics is too complicated compared to other interpretations.

The second option concerns Bell's inequality and its implication of hidden variables being untenable. This objection is an uninformed objection, and it was included to see if some objections to the interpretation stem from ignorance rather than an informed opinion. The third option relates to the explicit nonlocality found in bohmian mechanics. The fourth option pertains to the all-pervading quantum potential that guides the particles, and changes instantly everywhere. The last option is other reasons than the ones listed here.

It is rather striking that only a minority of the participants consider nolocality a reason for not supporting the interpretation. This is often cited as the biggest problem of the interpretation. Furthermore, the price one has to pay to formulate an interpretation, that has the feature of realism, is locality. Thus, the survey indicates that physicists could be open to another fomulation of quantum mechanics that had the feature of realism. Indeed, it was Bohm's intention to show that a hidden variables interpretation was possible.

> "*it should be kept in mind that before this proposal was made there had existed a widespread impression that no conceptions of hidden variables at all, not even if they were abstract, hypothetical, and "metaphysical," could possibly be consistent with the quantum theory ... it was therefore sufficient to propose any logically consistent theory that explained the quantum mechanics through hidden variables, no matter how abstract and "metaphysical" it might be. Thus, the existence of even a single consistent theory of this kind showed that whatever arguments one might continue to use against hidden variables, one could no longer use the argument that they are inconceivable. Of course, the specific theory that was proposed was not satisfactory for general physical reasons. But if one such theory is possible, then other and better theories may also be possible. And the natural implication of this argument is "Why not try to find them?"*" [26]

Other than nonlocality, it seems that the complexity of the interpretation and some of its metaphysical implications, such as quantum potential guiding all particles, seems too far-fetched. Judging the complexity of the formulation is of course a subjective matter, however, it is worth remembering that bohmian mechanics only assumes the Schrödinger equation and the guiding equation, which in turn makes it possible to derive Born's rule, leading it to have fewer assumptions than the Copenhagen interpretations. The quantum potential can certainly as well be viewed as an extra degree of complexity, but the notion of the quantum postulate must have seem just a far-fetched in its early days. One cannot help but wonder if the disregard for the notions implied by other interpretations, than the standard Copenhagen interpretation, simply stems from the fact that it is new. Quantum mechanics has so many strange, novel and non-intuitive features, that any interpretation of it must also include some radical implications. Maybe its only because we as physicist, are brought up with the Copenhagen interpretation, that we seem more comfortable with its implications. Remember that it was only those who did not declare their unfamiliarity with bohmian mechanics, who could answer this question. Still there are 21% who regard the theory as impossible because of Bell's inequality. This clearly shows a level of ignorance regarding alternative interpretations of quantum mechanics.

Question 17

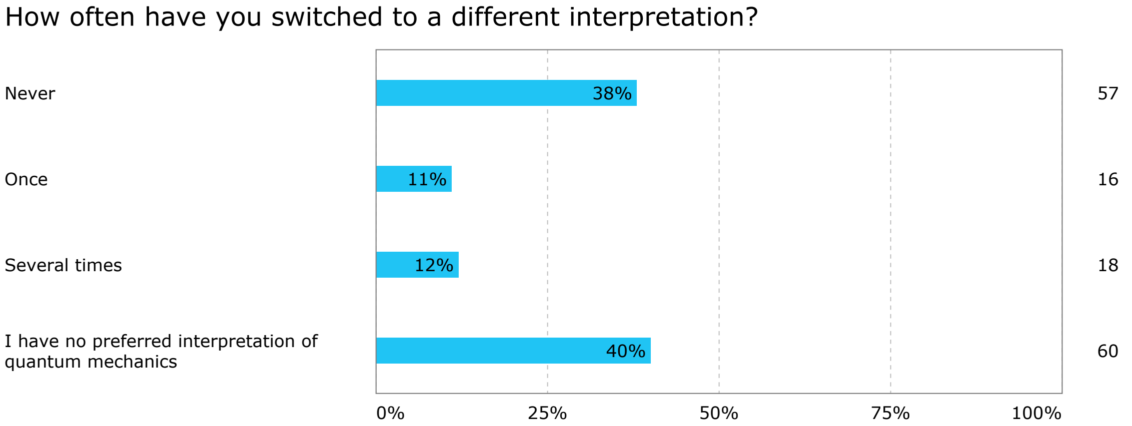

Figure 19: Distribution of all the participants' answers to question 17

The seventeenth and last question concerns the nature of changing interpretations, whether this is frequently done or never done by physicists and is taken from Schlosshauer et Al. The first option is for those who have never changed interpretation, which would be thought to include those who have not felt this as a pressing issue, therefore, not investigating other interpretations than the one presented to them, when they were first taught quantum mechanics. It could reveal that the preference of the first presented interpretation is quite inert. The second option is for those who have changed once, giving the interpretation of the theory some thought and investigating other interpretations. The third is for those who have changed interpretations several times and again for those who feel that the question of interpretation is important. The last option is for those who have no preferred interpretation. There is an overlap between the last option and the first one.

The results show that preferences of interpretations are very inert, since a clear majority, almost 80%, have never changed interpretation. Another way to regard this results is that the subject of quantum interpretations simply do not occupy the minds of physicists, or at least it is not given much attention in their minds. Does this reflect upon the topic of interpretation itself? It could be argued that nothing would change if an interpretation was abandoned for quantum mechanics, it still provides us with predictions that have never been refuted. Or does it reflect upon the physicists and the environment they are educated in? As physicists we are educated in an environment where the application of quantum mechanics, and even more so for just a specific formalism, plays a tremendous role in almost all branches of physics. The fact that a clear majority declared, in question 9, that interpretations of physical theories are important, would hint towards the latter. Is there time to discuss interpretations in physics, since it offers no role with regards to application? Are questions concerning the interpretations and foundations encouraged or dissuaded? The results here show that the subject is not reflected upon by the individual physicists, regardless of what the reasons may be.

Chapter 10

Correlations and Perspective

1 Correlations

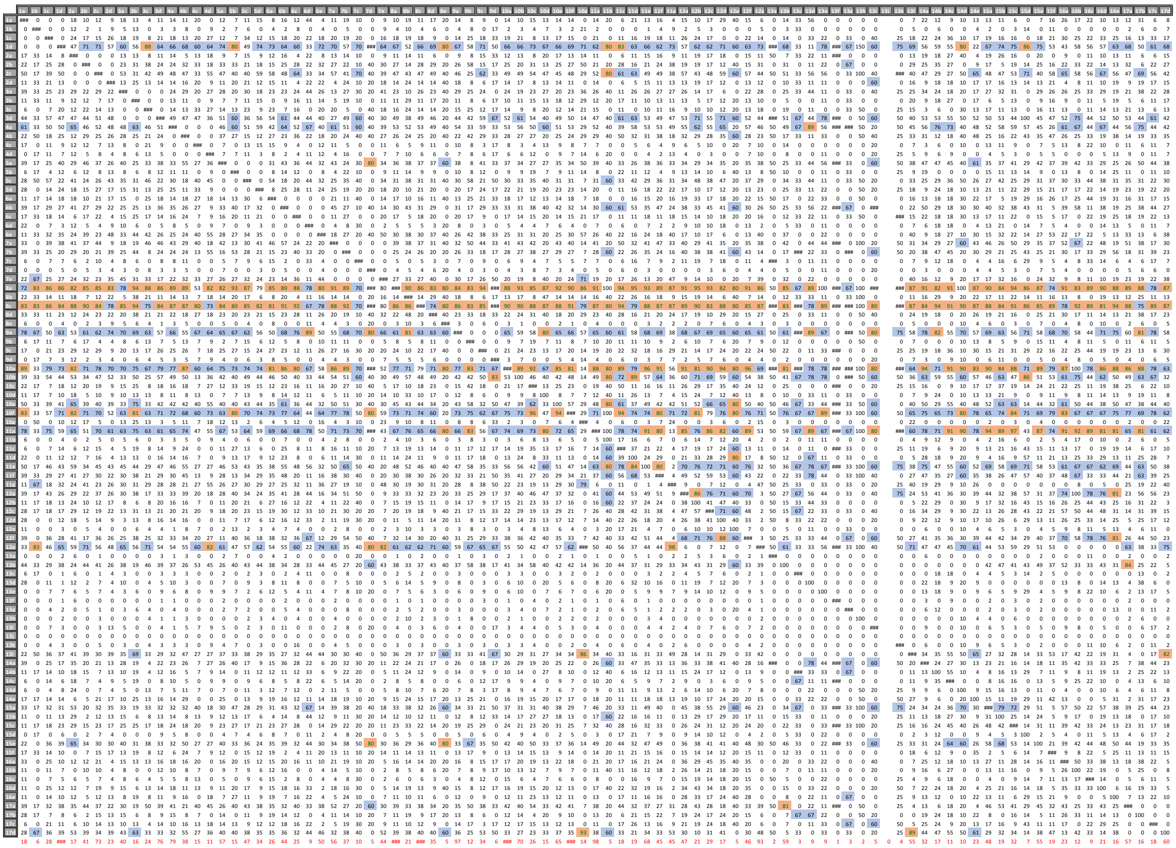

Figure 20: The figure is the correlation table of the survey. The participants are grouped according to which options they took in the survey horizontally. What each of these groups answered is displayed vertically. The numbers are percentages, and the size of each group is displayed at the bottom. The red colors represent correlation of 80% and more, while the blue colors represent correlations of 60 - 80%.

The figure above highlights some of the correlations found in the survey. Each column pertains to a specific option in one of the questions in the survey. The percentage of those who chose this option, and who chose other options are displayed down the column. The color codes have only been applied for options that had more than 10 participants choosing the option, as percentages would not be representative for small sample groups.

- Of the participants who don't have a preferred interpretation of quantum mechanics, 58% have expressed that they still feel that interpretations are important since it helps us describe nature. This implies that over half of the participants who do not have a preferred interpretation of quantum mechanics, feel that there is no satisfactory interpretation of quantum mechanics as of yet. This conclusion assumes that these participants have researched other interpretation than the conventional interpretation, an assumption that could be challenged when noticing that 22%, 40% and 71% of these participants have not formed an opinion of what characterizes the Copenhagen-, the many worlds interpretation or bohmian mechanics.

- Trough the correlation table, two color coded lines are seen. These represent the desired properties of a physical theory; consistency and simplicity. The only option that does not have over two-thirds preferring the property of simplicity are those who believe that macroscopic superpositions are possible in principle. There does not seem an obvious connection between the two, other than that macroscopic superpositions are perceived as complicated. The group consists of only 15 participants, thus it is not very representative. There is however not one option that has less than two-thirds preferring consistency as property of a theory.

- There is a strong correlation between the options "physical properties are not well-defined prior and independent of measurement" and that "the Copenhagen interpretation is characterized by indeterminism". Thus, ill-defined properties are seen in strong connection of the indeterminacy of quantum mechanics, which seems very much in line with Bohr's concept of complementarity.

- Other general trends, which are seen as lines, are the notions that randomness is a fundamental concept of nature, that the question "where is the electron?" is a meaningless question and that superpositions of macroscopic objects are in principle possible.

- Of those who favor the Copenhagen interpretation, 81% have never changed their preference of interpretation, giving a clear indication that the Copenhagen interpretation is still the standard interpretation taught. However, 7% of these participants have changed their preference once, implying that their standard interpretation in their class on quantum mechanics was not the Copenhagen interpretation.

- Of those who do not know the Copenhagen interpretation well enough to have formed an opinion, there is a strong correlation of not knowing the many worlds interpretation and bohmian mechanics, which could be taken as highlighting a shut-up and calculate approach.

2 Perspective

From the survey one can see that the Copenhagen interpretation is still the most popular interpretation. However, the answers, of those who favor the Copenhagen interpretation, to other questions show that what they regard as the Copenhagen interpretation is not necessarily the Copenhagen interpretation of either Bohr or Heisenberg. Indeed the answers the participants chose for the various questions, show that many see the wave function as being ontic, describing a quantity in physical reality. This was neither what Bohr nor Heisenberg thought. Furthermore, it is seen that quantum foundations do not play a significant role in the mind of an ordinary physicist. Indeed, the ignorance concerning foundational issues, such as the measurement problem and Bell's inequality, are quite significant. This ignorance does not come solely from the opinion that interpretations are not important, since over half of the participants felt that interpretations play a central role in describing nature. One can then ask how this ignorance to foundational issues and concepts has arisen. Obviously the participants' interest in interpretations has not been substantial enough to make them study the issues themselves, but if one has the impression that one understands a theory, one would not see the benefits of studying such issues. This impression can easily be imagined to arise, when one takes a course in quantum mechanics, where foundational issues are rarely touched upon, so one is inclined to think that the interpretation is rather straightforward. This also explain the fact that the survey showed that many take a quantum fundamentalist approach to the theory. Indeed this seems as the natural course when linking the physics courses one have had up to that point, i.e. the fact that all the physics taught prior to quantum mechanics consist of ontological theories [1]. To change this, to make physicists have sound knowledge of quantum mechanics, would require that it was taught in courses and that foundational issues openly talked about, and questions not quickly dismissed as meaningless. Why aren't quantum foundations discussed in quantum mechanics courses? One answer could be that quantum mechanics is so radically different from any other theory, therefore getting students to believe and apply the theory, requires a fundamentalist approach.

Now all this is of course conjecture based on a survey. Being at the center of this survey and discussing these issues, it is quickly realized that many engage in conversation with the clear opinion and knowledge of these issues.

Furthermore, it is argued that studying the foundations of our theory can help us move forward, perhaps some interpretations lend themselves better to constructing a quantum description of gravity. An analogy could be made to Kepler's laws[2]. They gave very good predictions, but lacked any interpretation since they were mere empirical formulas. The search for the underlying interpretation, or physics, and not simply being satisfied by mathematical tools that gave correct predictions, lead to the advent of Newtonian mechanics.

The answers show a great support to the fundamental ideas of standard quantum mechanics, such as indeterminism and that physical theories need not be ontological. The break from classical mechanics is becoming more obvious, a question then arises whether it is because more have seen the light, or that the environment in the physical community drags more people down in the mud? Some of the notions of classical mechanics and physical intuition are being completely abandoned, and the response for those who persist

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[1]Assuming one has not had a course in statistical mechanics before quantum mechanics.

[2]Altough quantum mechanics carries much more predictive power, and has even been used to predict and describe new phenomenon.

by them, can be very down putting. The response "the question is meaningless" is in general very discouraging, more so to a question as “Where is the electron?” Such answers would seem very harsh if one were to ask where is my candy? Of course this answer was in the context of very directed answer-options, but at the same time it is a sentence heard during classes in quantum mechanics, and seems very dissuading of ones notion of how everything is. At the same time of course, one should not lend too much credence to ones perception of the world, else the stars would still be attached to spherical shells with the Sun revolving around us.

Chapter 11

Conclusion

The thesis has shown the different features of three different interpretations, specifically the Copenhagen interpretation, the many worlds interpretation and bohmian mechanics. Furthermore, the opinions and attitudes of physicists have been examined, and it has been found that the Copenhagen interpretation still dominates as the most popular interpretation. However, the picture physicists have of this interpretation is not in accordance with the picture Heisenberg or Bohr had. One of the reasons for the popularity of the interpretation is its vagueness, which allows it to encompass a large variety of opinions.

The survey also showed that physicists are not in general familiar with foundational issues of quantum mechanics, though they still feel the question of interpretation is important. This then leads to questions of how these problems of interpretation of physical theories should be handled in physics. The survey shows that it is an issue that is important to physicists, but one that is not reflected in the courses related to quantum mechanics.

At the advent of quantum mechanics it was thought that it was not possible to formulate theories that preserve some of the cherished notions of classical mechanics, such as well-defined physical properties, determinism, objectivity and ontology. Some even claimed to have had proofs that it was not possible. These have since been proven wrong and today we have a plethora of interpretations. There is a great deal of subjectivity in the preferences of interpretation, unlike physics itself that strives to be objective. It could seem as a fitting solution to the issue of finding the "right" interpretation of quantum mechanics, that physics should embrace subjectivity and let the question of interpretation be a choice of personal opinion and preference. However, it is worth recalling that physics does not yet have a description of quantum gravity. Though the most of the interpretations give the same results, they are in reality different theories. If one could construct a viable theory of quantum gravity and corroborate it in the scheme of a specific interpretation, one could find the answer to the issue of interpretation that probably would satisfy most physicists. In this sense it does not seem as a waste time that physics should concern itself with the issue. Indeed, exciting prospect may lie waiting.

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