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Quantum Measurement, the Simplest Interpretation

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Abstract

Many different interpretations of the Quantum Theory have appeared over the one hundred years since its first formulation. The paper presents a detailed physical analysis of the process of quantum measurement, which is crucial in the development of a sound interpretation of the theory. The process of quantum measurement can be decomposed into three elementary steps, and the projection of state (or collapse of the wave function) is applied at the last step, the reading of the result of measurement by an observer. This determines a crystal clear simplest interpretation of the process and the alternative interpretation, supported by many interpretations of the theory, is obviously much more complex, so that Ockham's razor can be applied. Once this is established, a corresponding interpretation of the quantum state follows. We discuss some important issues as the superposition of states (or Schrodinger cat states), the wave particle duality and the non-local process associated to entanglement. In conclusion, many of the proposed interpretations of Quantum Mechanics appeared along the last decades can be firmly rejected, but there are open questions.

Subject Areas

Quantum Mechanics, Quantum Physics

Keywords

Quantum Measurement, Projection of State, Collapse of the Wave Function, Interpretations of Quantum Mechanics

1. Introduction

It is very disappointing that after almost one hundred years since the formulation of the Theory of Quantum Mechanics [1]-[3] the scientific community has not arrived to a consensus about the simplest interpretation of the process of quantum measurement, the projection of state or collapse of the wave function.

The enumeration and classification of interpretations of quantum theory is “a map of madness” [4]. It is almost impossible to list all the bibliography about different interpretations of the Quantum Theory, and of the process of quantum measurement. [4] contains some of the most relevant publications. In the former reference the interpretations are classified into two main classes, type I (in the reference terminology) and type II, according to the character of quantum states. Type I (intrinsic realism) are interpretations in which the quantum state is a faithful representation of a physical entity, that is, quantum probabilities are determined by intrinsic properties of the system; on the other hand, type II interpretations (participatory realism) are interpretations in which the quantum state represent the (limited) available information about the state of the system. Interpretations of the process of quantum measurement are closely related to the former alternatives, it is either a physical process of the system or, contrarily, a process of update, reset of the available information about the system. For example, in the many worlds interpretation [5], the measurement is a physical process, it generates multiple universes, and in “our” universe there is a singular and discrete physical evolution of the state of the system, which happens to be an exception because it is non Hamiltonian. In the so-called Copenhagen interpretation or in the Qbism [6] [7] the projection of state is not a physical process of the system, but an (informational) change of state of the mind of the observer.

Ockham’s razor is a golden rule that applies to many different fields; when a set of data is explained through alternative theories or stories, the preferred alternative is the simplest one. It is a kind of economy of hypothesis, and in many situations the simplest alternative is also the more probable. In Science it can be applied to different theories reproducing the same observational and experimental data, but it can also be applied to different interpretations of the same scientific theory. Although all interpretations preserve the scientific content of the theory, the observable predictions, it can be an advantage to have a preferred interpretation, for example when going beyond the theory, when trying to explain new experimental data that do not fit in the theory.

The aim of this work is to carry out a careful physical analysis of a typical process of quantum measurement, adequately decomposed into elementary steps. At some point we will be confronted with two opposite alternatives and, at that point, Ockham’s razor will be applied. The two alternatives determine different hypotheses and it is crystal clear which one is simplest. After the selection of an interpretation of the process of measurement it is discussed some consequences about the character of the quantum state.

2. Quantum Measurement

A quantum measurement is similar to a classical one, but the measured system is microscopic and the measurement apparatus must be designed to enhance the reaction caused by the interaction of the measured system with a (microscopic) subsystem of the apparatus. Such enhancement is not usually needed in a classical measurement. On the other hand, the result of a classical measurement is clearly an update of the available information about the state of the system; it is not expected that the presence of an observer (which reads the result) could exert any influence in the physical process of the measured system, that is, there is an interaction of the measured system with the apparatus but not with the mind of the observer. The main question in a quantum measurement is if the rule of projection of state is a physical process of the system or just an update of information as in the classical case. A typical quantum measurement can be decomposed into three main elementary steps, associated to the corresponding (physical) processes that consecutively happen.

First, an interaction takes place between the measured quantum system and a microscopic subsystem of the measurement apparatus. At this stage the projection of state does not apply; it is not possible to distinguish this interaction from other microscopic interactions taking place all the time and everywhere, and which do not evolve into a measurement. Obviously, the effect (projection of state) can not precede the cause (completion of the measurement process).

Second, the change of state of the subsystem is enhanced, through some kind of chain reaction, into a macroscopic signal, a macroscopic, observable change of state of the measurement apparatus. There is an unavoidable temporal gap between steps one and two, the generation of the macroscopic signal takes some time, which depends on the specific technique of the measurement apparatus. Along this time the quantum system can interact with other systems with which it could become entangled. The projection of state does not take place now, there is not a sharp boundary between microscopic and macroscopic that could determine the application of the projection of state.

Finally, a human agent reads the macroscopic signal and associates it to a particular value of the measured physical magnitude. In standard quantum mechanics this is the step in which the projection of state applies. The first system in which the projection of state takes place is the brain of the observer. The temporal gap between steps two and three is highly variable, from an almost simultaneous reading to the generation of the macroscopic signal to a much longer time gap if, for example, the signal is recorded and read hours or days later. Along this time gap both the quantum system and the measurement apparatus can become entangled with other systems. The projection of state must apply to both quantum system and measurement apparatus, and to any other system entangled with them.

We are interested in analysing the possibility that the projection of state could be a physical process of the measured quantum system. The unavoidable temporal gap between steps one and three makes this option very problematic. Some consequences of the interpretation of the projection of state as a physical process of the quantum system are the following.

It means the existence of a specific, exceptional and discrete time evolution law for quantum measurements, against the generic (universal) Hamiltonian law in

Quantum Mechanics.

There should be some signal emitted by the brain of the observer and detected by the measured system, the measurement apparatus and any other system entangled with them, able to generate the physical process of projection of state. The quantum system could have disappeared along this time interval.

We can ask which macroscopic signal goes from the measurement apparatus to the brain of the human agent. If the projection of state, a hypothetical physical process, has not taken place at stages one and two, the projection of state of the system and the following emergence of the macroscopic signal can not be real before the reading of measurement, they are just potential possibilities among others corresponding to different results of measurement. Does a potential possibility collapse into a real signal in the brain of the observer when it is read, detected? Is this collapse transmitted to the apparatus and only then becomes a real, physical signal (after having being observed!)?

The evolution of the universe previous to the appearance of the first observers must have happened without a single projection of state. Taking into account that there is not boundary between microscopic and macroscopic systems, the whole universe must have been in an entangled state with many different potential possibilities. The first measurements must have generated a monumental collapse, projection of state.

If a conscious being sees the macroscopic result of the measurement, but it is not a human being (or a physicist!) is there a projection of state? Not everybody will be able to associate the macroscopic signal with a specific value of the measured magnitude.

An alternative explanation becomes much simpler: the projection of state is exclusively a physical (chemical, biological) process in the human agent's brain, mind, and it can not exert any physical influence in the measured quantum system. When the observer reads the result of measurement the available information about the physical state of the system can be updated, so that the collapse of the wave function is not a physical process of the quantum system, but a reset of information in the agent's mind. The projection of state is in this interpretation simultaneous to the reading of the measurement result, and it is just a change of available information. There is no need of a mysterious signal sent from the brain of the observer to the quantum system; the projection of state applies to the quantum system, the measurement apparatus and any other system entangled with them as an update of information about their physical states. In this interpretation the Hamiltonian evolution law is really universal and the quantum measurement is not an exceptional physical evolution law. What happens after the quantum measurement is a change of initial condition (projected quantum state as the new available information about the physical state of the system) for the next Hamiltonian time evolution. If we consider a classical statistical theory, the result of measurement applies as a conditional probability: the new information restricts the set of possible events, discarding those with other values of the physical magnitude, and the corresponding distribution of probability must be restricted to the set of possible events in accordance with that. Quantum mechanics is obviously a statistical theory (and something more), and we can consider it as a golden rule to interpret the theory as similar to a classical statistical one whenever possible, because this is the simplest interpretation. In the case of measurement, the projection of state represents the application of a conditional probability, that is, the quantum state represents an ensemble (and not a single system), and the result of measurement restricts it to a subensemble. This interpretation of the projection of state makes it necessary to analyse with care the meaning of the quantum state, because when we apply the projection of state there is a change of quantum state (subensemble) but the (unknown) physical state of the system does not change.

3. Interpretation of the Quantum State

The measurement is a process in the brain of the observer without any interaction with the measured system. Therefore, we can not understand the quantum state as a physical reality, it is just the information available about the state of the system, that is, a mathematical tool in the theory of Quantum Mechanics representing a statistical ensemble of systems. We should distinguish between the physical state of the system and its quantum state; because of the quantum laws the physical state of the system is only partially known, and this partial knowledge is encoded in the mathematical quantum state of the theory. Along any interaction there is an unknown change of the physical state of the system, as well as a known evolution of the quantum state determined by the Hamiltonian evolution law. If the interaction evolves into a measurement, we get new information about the state of the system (right after the interaction) which is reflected in the new (projected, conditional) quantum state.

It is surprising and mysterious that a single complex distribution of amplitude of probability, in other words, a ray in a Hilbert space, can encode different joint distributions of probability corresponding to a family (!) of statistical ensembles, one for each maximal set of compatible physical magnitudes, represented by commuting self-adjoint operators in the Hilbert space. In principle, the corresponding joint distribution of probability is observable, because the joint measurement of compatible magnitudes is consistent, *i.e.*, the measurement of a magnitude does not modify the value of other commuting magnitudes. There is not an established mechanism in the theory to determine joint probability distributions for sets of incompatible (non-commuting) magnitudes, and in some cases, it can be mathematically proven that such a joint distribution does not exist [8]. If Quantum Theory contains the maximal allowed information about the state of the system in a given context, it is quite possible that there are many other cases, many other quantum states, and not just the one considered in Bell's theorem, in which a joint probability distribution for incompatible magnitudes (*e.g.*, a maximal set of independent magnitudes) does not exist. For example, if we consider a maximal family of independent magnitudes (in classical mechanics it would determine a unique physical state) a hypothetical joint probability distribution would not be observable, because joint measurement of incompatible magnitudes is not consistent, *i.e.*, measurement of a magnitude perturbs the value of other non-commuting ones. The quantum state (or quantum ensemble) is not a classical statistical ensemble, but a family of statistical ensembles, with observable joint probability distributions. We can say that the statistical side of Quantum Mechanics is a theory of observable joint distributions of probability. There is an additional information in the quantum state, and it is the relative phases between the complex coefficients that express the quantum state as a linear combination of eigenstates. This last information is crucial in the description of the wave particle duality.

3.1. Superposition of States

In a quantum state made of a superposition of two states corresponding to two different values of a physical magnitude (*e.g.*, position) the golden rule says that we should interpret, when possible, this quantum state as a statistical ensemble, in which some systems have the first value of the physical magnitude and others have the second value. A well-known thought experiment, Schrodinger's cat [9], illustrates this interpretation. If the cat where in a physical superposition of two states (dead and alive), that is in some "new" physical state of superposition or in both physical states simultaneously, when the box is opened the external observer should see this physical state, a projection of state should happen in his brain and a signal should be sent to the cat generating the projection of physical state into a classical one, either dead or alive. On the contrary, if the quantum state of superposition represents a statistical ensemble, the cat is always either alive or dead, each state corresponding to a subset of the ensemble. When the box is opened, the observer determines to which subset of the ensemble belongs the particular cat in this run of the experiment. A statistical repetition of the experiment would show a representation of the whole ensemble, with a fraction of cats alive and another fraction dead. It is very clear which interpretation is simpler. Moreover, if in the first interpretation we add an observer inside the box, the cat is either dead or alive for this observer while both cat and observer should be in a superposition of states for the external observer previously to the opening of the box. Which observer is right? Obviously, the observer inside the box has more recent information about the state of the cat. Unless we believe in a mysterious signal sent by the brain of the observer to the cat, the inside observer can not exert any influence in the physical state of the cat, and we should prefer the information of the inside observer. Without inside observer we must accept that the external observer has only partial (statistical) information.

3.2. Wave Particle Duality

The wave particle duality is one of the most astonishing properties of microscopic systems, elementary particles, atoms, molecules, ... In some experimental circumstances, when the spatially localised microscopic system can follow two or more trajectories which later on rejoin, it is observed a typical wave behaviour of superposition and interference. In Quantum Mechanics, the description of this phenomenon is that the amplitudes of probability (complex numbers) associated with different trajectories are added in the joining point and, as complex numbers, they have both modulus and phase, so that relative phases between different components give an account of a wave like superposition and interference, sometimes the total amplitude increases and others it diminishes. This astounding phenomenon has generated different interpretations. Sometimes it is said that a microscopic system is neither a particle (corpuscular, spatially localised system) nor a wave (spatially distributed), but something different, a quantum entity. However, there is not a sharp limit between microscopic and macroscopic systems; in fact, experimental improvements have shown this wave like phenomenon in larger and larger molecules.

In the two slit experiment, there is a source of electrons with fixed velocity. The electrons are directed towards a first screen with two parallel slits. Some electrons go through the slits and arrive to a final screen where they are detected as dots. The distance between the slits is chosen (according to the velocity of the electrons) to enhance the visibility of the interference pattern, which appears because of the wavelike behaviour of electrons [10]. After enough repetitions of the experiment (a statistical sample) there appear some bands with maximal density of dots and others with minimal density, in a typical interference pattern. In the quantum description we associate an amplitude of probability to each slit, and its superposition at the final screen gives way to the interference pattern. Particles (spatially localised systems) behave as waves.

If now one of the slits is blocked, only electrons following the open slit arrive at the final screen (indirect measurement of position). In the quantum description there is only one source of amplitude of probability, the open slit, and there is no more superposition and interference. We observe (using a statistical sample) a normal diffusion pattern, with a central area with high density of dots and lower densities when the distance to the center increases. The interference pattern does not appear.

A careful physical analysis of the two slit experiment, decomposed into elementary steps, is developed in the following [11].

In the first part of the experiment the electron enters the experimental set up, and after some interactions it arrives to a final state (position at the final screen) where it is detected. In a statistical sample, it is observed that an interference pattern appears.

In the second part of the experiment the final state (final position) of the particle is different. The change of final state can not be detected in a single run, we need a statistical sample to check that the interference pattern does not appear. We can infer that the electron has followed a different chain of interactions, that is, at least one interaction must have been different. Only a different evolution can explain a different final state.

The origin of this new interaction(s) must necessarily be the unique additional element in the experimental set up, the blocking system. The only way a system can exert some influence in a process is through interaction.

We can also infer the trajectory of the particle in the second part of the experiments. The particle can arrive at the final screen only if it follows the unblocked path, the open slit. There is a spatial separation between the system blocking one slit and the particle going through the other slit.

We must conclude that particle and blocking systems do not have a local interaction, they are spatially separated. Some other (new) systems must play the role of intermediate element allowing an indirect interaction between particle and blocking system.

The simplest hypothesis is that a wave follows both slits of the experiments, and that the corresponding wave component is blocked in the second part of the experiments by the additional blocking system. In the first part, when both components of the wave arrive at the final position, there is superposition and interference, giving way to the interference pattern, because there is destructive interference at some regions of the final screen. We must understand that there is some correlation between amplitude of the wave and probability of finding the particle. In the second part of the experiments one of the components of the wave is blocked and there is no more superposition and interference, so that particles arriving to the final screen do not distribute in an interference pattern, but in a usual diffusion pattern.

We need an additional system, a distributed system or wave, to intermediate in the indirect interaction between the electron and the blocking system. A simple hypothesis is that the de Broglie wave length associated with elementary particles and other microscopic systems is the wave length of a real, physical wave accompanying the spatially localised particle. When the two slits are open, the wave going through both slits superposes in the final screen and generates the interference pattern, understanding that in some way the wave guides the electrons, and modifies the geodesics. When one of the wave components is blocked there is no more superposition and interference, so the interference pattern does not appear.

A distributed system of very low energy density but distributed along the whole space time is a natural candidate for dark energy. See in [11] a simple mathematical model for this new field. Obviously, the existence of a new distributed system offers a rational explanation of the wave particle duality.

3.3. Entanglement

Sometimes, when two systems interact they become entangled, *i.e.*, some physical magnitudes of both systems become correlated. A simple example in Classical Mechanics is the collision of two particles (*e.g.*, spherical balls) in a horizontal plane. Because of the conservation of momentum, the sum of final momenta of the two particles is fixed, equal to the total initial momentum. We can determine the momentum of one ball without exerting any measurement over it; we can measure the momentum of the other ball and compute (infer) the corresponding momentum of the unmeasured ball.

In Quantum Mechanics there are also well-known examples of entanglement. A famous example, because of the analysis of Bell, is the generation of two identical particles in a total null spin state. There is perfect anticorrelation between the spin values (up or down) of both particles in the same spatial direction. And this perfect anticorrelation appears for all spatial directions. Therefore, we can infer the value of spin of one particle in a given spatial direction by measuring the spin of the other particle. Then, by measuring the spin of the first particle in another spatial direction we get the values of spin of the particle in two different directions (at least, previous to the measurement), even if these two spin magnitudes are incompatible, do not commute. Obviously, the spin operators of two different particles commute, and therefore are observable.

A simple hypothesis to explain the anticorrelation is that the values of spin in arbitrary directions of both particles are fixed at the generation event. Imagine we could know the values of spin in a family of spatial directions (three or more). After a repetition of the experiment we would get a table of relative frequencies for these spin values, approaching some distribution of joint probabilities for this family of incompatible magnitudes. Obviously, the marginal relative frequencies for two chosen spatial directions should reproduce the observed values for the observable joint distribution of probability in two directions, the values predicted by Quantum Mechanics. This analysis is obviously theoretical, hypothetical, because this table of relative frequencies in three or more directions is not observable. Bell's theorem [8] proves that such joint distribution of probabilities (or relative frequencies) for three or more spatial directions does not exist. We should conclude that the values of spin in arbitrary directions are not fixed at the generation event, so we could expect that these values are generated at the measurement event.

Notice first that if this is the case, if the value of the physical magnitude involved in the initial interaction of a measurement is generated along the interaction and previously it is undefined, this should be generalised to all interactions, and not just interactions that evolve into a measurement. This is because the initial microscopic interaction that later on evolves into a measurement can not be distinguished from other interactions that do not evolve into measurements. The measurement happens in the mind of the observer, it is posterior to the initial microscopic interaction and it can not exert any physical influence over the measured microscopic system.

This new hypothesis confronts what we know about Special Relativity. The two spin measurement events can be spatially separated, in the terminology of special relativity. This means there is not a well defined temporal order between them, one of the measurements is previous in some reference frames and posterior in others. Then, how can "inform" one measurement event of its result of measurement to the other event, in order to preserve the perfect anticorrelation? No physical signal or process can connect two spatially separated events. Sometimes it is argued that special relativity does not apply in this specific context, without giving a consistent physical argument for that. A hypothetical process travelling at a speed higher than c in a given reference frame is seen in another reference frame as following the same trajectory but in an opposite spatial direction! Even if there were a special, preferred reference frame, *e.g.*, the laboratory frame, the two measurement events could be simultaneous in this frame, making it impossible to send a physical signal from one to the other. The explanation of perfect anticorrelation can not be a process in space time. A very risky hypothesis would be that there is some bidirectional connection between the measurement events through a fifth dimension. Taking into account that, once fixed the "first" measurement event the second one can be either spatially or temporally separated, and the boundary between both cases is just mathematical, theoretical (determined by the first event), without physical relevance, we must conclude that the same type of bidirectional connection should be established between the measurement events even when they are temporally separated. This hypothetical fifth dimension should be able to bidirectionally connect two arbitrary events of space time, of the whole universe, and this hypothesis is too heterodox to be accepted.

There are probably many quantum states for which there does not exist a joint probability distribution for incompatible magnitudes, and in many cases, this property will not be related to any kind of non-locality. We do not understand how it can be, the heart of Quantum Mechanics can not be explained. We can insist that the former process of perfect anticorrelation is a non-local one, but we do not understand how it is possible.

4. Summary

The process of quantum measurement has essentially two alternative interpretations: either the projection of state is a physical process of the measured system or it is an update of information, a mental process in the mind of the observer, without physical consequences for the measured system. We have analysed both alternatives and the conclusion is that the second interpretation, update of available information about the state of the system, is clearly much simpler than the other; Ockham's razor states that this interpretation should be the preferred one. We have also analysed some consequences of this interpretation with regard to the interpretation of the quantum state (a probabilistic description of the physical state of the system), superposition of states, etc.

In particular, we have analysed the wave particle duality and concluded that there must be a new physical system, de Broglie wave, which offers a rational explanation of the property. This is not a question of interpretation, but a true scientific prediction. The existence of a distributed system, of very low energy density and distributed along the whole space time is a natural candidate for dark energy.

The most profound mystery of Quantum Mechanics is that (probably in general) there are not joint distributions of probability for incompatible magnitudes, in particular for a maximal family of independent magnitudes that could determine univocally the physical state of the system, in clear contrast with Statistical Classical

Mechanics. We have analysed the state of entanglement of two identical particles in a total null spin state and we have found a deep contradiction: it is concluded, grounded in Bell's theorem, that the values of spin can not be fixed at the generation event, while it is also highly speculative to state that there is a non-local process able to explain the perfect anticorrelation.

Conflicts of Interest

The author declares no conflicts of interest.

References

[1] Heisenberg, W. (1925) Über quantentheoretische Umdeutung kinematischer und mechanischer Beziehungen. *Zeitschrift für Physik*, **33**, 879-893. https://doi.org/10.1007/bf01328377

[2] Schrödinger, E. (1926) Quantisierung als Eigenwertproblem. *Annalen der Physik*, **384**, 361-376. https://doi.org/10.1002/andp.19263840404

[3] von Neumann, J. and Wheeler, N.A. (1932) Mathematical Foundations of Quantum Mechanics. New Edition (2018), Translated by Robert T. Beyer, Princeton University Press.

[4] Cabello, A. (2017) Interpretations of Quantum Theory: A Map of Madness. In: Lombardi, O., Fortin, S., Holik, F. and Lopez, C., Eds., *What Is Quantum Information*, Cambridge University Press, 138.

[5] Everett, H. (1957) "Relative State" Formulation of Quantum Mechanics. *Reviews of Modern Physics*, **29**, 454-462. https://doi.org/10.1103/revmodphys.29.454

[6] Fuchs, C.A. and Schack, R. (2013) Quantum-Bayesian Coherence. *Reviews of Modern Physics*, **85**, 1693-1715. https://doi.org/10.1103/revmodphys.85.1693

[7] Fuchs, C.A. (2002) Quantum Mechanics as Quantum Information (and Only a Little More). In: Khrennikov, A., Ed., *Quantum Theory: Reconsideration of Foundations*, Växjö University Press, 463-543.

[8] Bell, J.S. (1964) On the Einstein Podolsky Rosen Paradox. *Physics Physique Fizika*, **1**, 195-200. https://doi.org/10.1103/physicsphysiquefizika.1.195

[9] Schrödinger, E. (1935) Die gegenwärtige Situation in der Quantenmechanik. *Die Naturwissenschaften*, **23**, 807-812. https://doi.org/10.1007/bf01491891

[10] De Broglie, L. (1923) Waves and Quanta. *Nature*, **112**, 540-540. https://doi.org/10.1038/112540a0

[11] López, C. (2024) Wave Particle Duality: De Broglie Waves in Indirect Quantum Measurements. *OALib*, **11**, 1-8. https://doi.org/10.4236/oalib.1111202