On the Interpretation and Philosophical Foundation of Quantum Mechanics

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Abstract

When investigating various interpretations of quantum mechanics one notices that each interpretation contains an element which escapes a complete and full description. This element is always associated with the stochasticity of the individual event in the quantum measurement process. It appears that the implications of this limit to any description of the world has not been sufficiently appreciated with notable exceptions of, for example, Heisenberg, Pauli and Wheeler. If we assume that a deeper foundation of quantum mechanics is possible, the question arises which features such a philosophical foundation might have. It is suggested that the objective randomness of the individual quantum event is a necessity of a description of the world in view of the significant influence the observer in quantum mechanics has. It is also suggested that the austerity of the Copenhagen interpretation should serve as a guiding principle in a search for deeper understanding.

In recent years, a significant increase of interest in the foundations of quantum mechanics can be observed. This increase is certainly related to the immense progress made during the last two decades in experiments with individual quantum systems. This technological progress has made it possible to really perform more and more of the famous gedanken experiments which were so important in the early days of the theory. Not only did these experiments confirm the theory in every detail, they also opened up avenues for new experimental directions which might even lead some day to new technology. While such applications are certainly still far away, areas like quantum cryptography[1], quantum computation[2] and interaction-free measurement[3], just to name a few examples, certainly deserve the attention they receive. All this activity has also drawn more attention to the problems of understanding and interpreting quantum mechanics. It seems that there, a definitive consensus has not yet been reached. As witnesses I quote authorities like Feynman as saying[4]: "I think I can safely say that nobody today understands quantum mechanics", whereby he apparently included himself, or like Roger Penrose[5], who describes his opinion remarking that while the theory agrees incredibly well with experiment and while it is of profound mathematical beauty, it "makes absolutely no sense".

Why did even physicists who have contributed so significantly to quantum theory - Feynman was even rewarded the Nobel Prize for one of its mathematical formulations - choose such emphatic and strong formulations? Why is it that the average physicist hears very little about such problems during his/her education? Why is the comprehension of the theory very often focused on formalism while questions that probe for deeper meaning are usually not tackled?

To take a closer look at the situation, let us turn to a brief analysis of the interpretation of quantum mechanics. We note that there are at least two levels of interpreting a formalism, a physical theory. The first, basic, level supplies the rules that determine which element of the formalism corresponds to which measurable quantity or to which observable fact in a concrete experimental situation. Theses rules are a large, mostly not explicated but only implicit, set of instructions. These instructions concern the manner of working with the statements of the theory in order to obtain predictions for future experiments or events, and they concern the instructions on how to proceed in experiment in order to demonstrate or test a theoretical prediction.

In the case of quantum mechanics we encounter, on this lower level, the statistical interpretation introduced by Born, which I propose to call statistical interpretation in the narrower sense. It maintains that the absolute square of the wave function represents the probability for observation of a certain result, for example, the probability for finding the electron within a certain volume of space. On this level of interpretation an almost complete consensus between physicists exists, since, as was pointed out in the above quote by Penrose, the predictions which can be obtained from theory applying this rule match all experiments perfectly. It is particularly the wide range of successful applications of the theory which is impressive, since quantum physics supplies predictions from the sub-atomic level all the way up to cosmological problems. As long as one restricts oneself to using quantum mechanics exclusively for solving questions of statistical prediction of experimental results one will never come across an interpretational problem. Indeed, it is reasonable to expect that one will find more and more perfect confirmations of the theory.

Are there, then, any problems, any difficulties? It seems that they arise just where concepts like *understanding*, *meaning*, or *sense* are dealt with. They appear when we ask what quantum mechanics might mean for our view of the world (*Weltanschauung*) or even when we ask questions after the why of the theory in a very broad sense. On this level there certainly is a problem. I propose to call this the interpretational problem of quantum mechanics in the broader sense, it is an interpretational problem on a metalevel.

As an interesting case from the history of physics I would like to mention Einstein's development of the special theory of relativity. It so happened that almost all relativistic equations which appear in Einstein's publication of 1905 were known already before[6], mainly through Lorentz, Fitzgerald and Poincaré - simply as an attempt to interpret experimental data quantitatively. But only Einstein created the conceptual foundations, from which, together with the constancy of the velocity of light, the equations of the theory of relativity arise. He did this by introducing the principle of relativity, which asserts that the laws of physics must be the same in all inertial systems. I maintain that it is this very fact of the existence of such a fundamental principle on which the theory is built which is the reason for the observation that we do not see a multitude of interpretations of the theory of relativity. We accept, for instance, that the equations of the theory inevitably imply that clocks really run at different speed as seen in reference frames which are moving relative to each other, and that this is indeed a statement about the relative course of time in these reference frames.

The situation is quite different in the case of quantum theory, where we do not have such a generally accepted principle which can serve as the foundation of the theory. Indeed, I would suggest that this is the very reason makes it possible that a variety of different interpretations - in the broader sense - coexist. It is important to notice that nearly all of these interpretations are in agreement with each other when it comes to definite experimental predictions. Therefore, as is to be expected for an interpretation in the broader sense, there is no way - at least not immediately - of experimentally differentiating between them. So, instead of trying to decide here which of these interpretations[7] is correct, I would propose here to attempt to learn from the fact that various interpretations coexist. For that purpose, we briefly sketch now the important features of a few interpretations existing today.

First, let us briefly investigate Bohr's formulation of the Copenhagen interpretation. In this interpretation we are dealing with a quantum phenomenon as a whole entity which comprises both the observed quantum system and the classical measuring apparata. Then it does not make any sense to speak about characteristics of the quantum system in itself without explicitly specifying the measuring devices. It is therefore even more senseless to assign to a quantum system simultaneously complementary attributes like position or momentum, since the apparata which are needed to measure them are mutually exclusive. For example, it is fundamentally impossible to build an apparatus which simultaneously measures both position and momentum to arbitrary precision and thus questions asking for simultaneously sharp values of complementary quantities make no sense. In the Copenhagen interpretation, the wave function is only our way of representing that part of our knowledge about the history of a system which is needed for calculating future probabilities for specific measurement results. And it should always be stressed that strictly speaking any statements are statements about the classical apparatus and its classical features and observables. To give an example, in the case of the double-slit-experiment the wave function makes it possible to calculate both the probability to find the electron passing through a certain slit and the probability for where it will appear in the interference pattern, while the observation of these probabilities always implies experimental arrangements which are mutually exclusive. An experimental prediction that surpasses this limitation is not possible in principle[8]. So it is especially impossible in principle to predict with certainty both through which slit the electron will go and where it will appear in the interference pattern.

An opposite position is assumed by the causal or ensemble interpretation - I am avoiding the common term "statistical interpretation" (in a broader sense), since this term is also applied to quite different positions[9]. The causal interpretation was originally proposed by Bohm[10] and deBroglie[11]. Bohm explicitly keeps the predictions of quantum mechanics while deBroglie would allow a change of the formalism. In this present work I am referring mainly to Bohm's position. According to Bohm, the wave-function supplies an additional potential - the quantum-potential, as he called it. This potential, when inserted into the Hamilton-Jacobi-equation of classical physics, leads to well determined trajectories of the individual particles. For the case of the double-slit-experiment, for example, each particle has a well-defined trajectory and passes through one of the two slits according to this interpretation. The interference pattern then arises because of the specific form of the quantum potential, which acts such that fewer particle paths end in the intensity minima of the interference pattern than in the maxima. This interpretation permits therefore - as opposed to the Copenhagen interpretation - to speak of the path of the particle even in those cases in which the experimental arrangement is such that the interference pattern is registered. Yet it is important to notice that this is connected with the fundamental impossibility to control the initial conditions. It is thus not possible, not even in principle, to select a specific trajectory for the particle through, say, a narrowing of the entrance slit because any change of the external boundary conditions results in a change of the quantum potential and thus in a completely new set of possible trajectories. It is therefore impossible to demonstrate the validity of the assumption fundamental to the deBroglie-Bohm interpretation, that any particle has a realistic trajectory.

Another, again very different, interpretation is Everett's Relative-State-Interpretation[12], which is usually called Many-Worlds Interpretation. Here all branches of the wave function exist at all times, wherefore it is claimed that no collapse of the wave function occurs. This interpretation maintains that there is a splitting of the universe into individual branches, whereby in each of those branches one component of the wave function is realized. Consequently, it is asserted that the observer, too, exists in each branch in a different state and is therefore also split. The concrete "I", my awareness, is hic et nunc in a well defined state and thus is to be found in a certain branch of the universe in which only one, namely a particular one of the possible results of the specific individual measuring process is realized. The many worlds interpretation thus is fundamentally unable to predict in which one of the branches I will experience finding myself. The claim that the observer coexists in many different states is intrinsically untestable.

This short, sketchy comparison of three different interpretations[13] which, again, lead to the same experimental predictions, tells us different things. Firstly, that physicists apparently are gifted with creative imagination. Secondly, that it is possible to connect a quantity with an ontic characteristic - namely existence - in one interpretation, while this is simply denied in another interpretation. For example, the deBroglie-Bohm interpretation associates with each individual particle both a well-defined momentum and a well-defined position at all times. As another example, Everett's interpretation speaks of the equal existence of all possible results of a measuring process. Both examples deal with assumptions which are flatly rejected by other interpretations that were mentioned. Thirdly and most importantly, each of the interpretations leaves at least one element unexplained. Namely, each of the interpretations fails when it comes to a complete description of the individual event. It should be noted that two more recent interpretations, the Transactional Interpretation[14] and the Consistent Histories Interpretation[15] also share this feature of an unexplainedness of the individual event. In the Transactional Interpretation the state vector is considered to be a real physical wave emitted as an "offer wave" based on the preparation procedure of the experiment. The interaction then comes to a close through the emission of the "confirmation wave" by what is usually called the collapse of the wave function. The quantum particle, e.g. the photon, electron etc., is then considered to be identical with the finished transaction. It is fundamental to that interpretation that where the closure of the transaction takes place is an unexplained input to the process. In the Consistent Histories Interpretation we have a similar situation because there the observed event again is a fundamental input in the sense that it determines the set of possible histories consistent with the observation made. There is no attempt to try to explain why a specific event happened besides on the basis of the consistent histories which had been constructed in order to be consistent with the observed event.

We have thus observed in our brief discussion that the individual event has a very specific role in quantum mechanics. While this is a natural feature of the Copenhagen interpretation, it resists any attempt at trying to explain it in the other interpretations in a way which goes beyond just fulfilling the requirements of consistency. This has to be so, since the formalism of quantum mechanics supplies no starting point whatsoever for the description of the individual event and all interpretations mentioned refer to the same formalism. With the notable exception of a quantum system in an eigenstate of the observable chosen, quantum mechanics only makes predictions with respect to the ensemble of many individual events. These are very precise predictions about the average of the measurement results expected, about their distributions and their statistical errors. The measurement problem can be distinguished into at least two parts. Firstly, the explanation why off-diagonal elements in a density matrix disappear and secondly, the explanation which specific event in the diagonal density matrix system is observed in an experiment. While there has been considerable progress in the last few years on the first question[16], it is well known that the second question cannot find an answer within linear quantum mechanics. It thus appears that quantum mechanics is not able to "explain why (specific) events happen" as pointed out by John Bell[17]. To again give a specific example there is no way to predict through which slit a particle will pass when incident on a double slit assembly.

The desideratum of explaining why a specific event happens has lead to numerous attempts of reformulating quantum mechanics such that it both is consistent with existing observation and that classical world naturally emerges from it. An early attempt by Bialynicki-Birula and Mycielski[18] maintains that a nonlinear term should be added to the Schrödinger equation which keeps wave packets from spreading beyond any limit. Experiments with neutrons[19] have resulted in such small upper limits for a possible nonlinear term of that kind that some quantum features would survive in a macroscopic world contrary to the initial intentions of the proposers. Another proposal for a nonlinear variant[20] has been shown[21] to make communication faster than light possible by exploiting Einstein-Podolsky-Rosen correlations between two particles. Finally, the so-called dynamical reduction program should be mentioned where it is proposed that the linear evolution of the Schrödinger equation should be supplemented by a nonlinear and stochastic process which would lead to a mechanism for wave packet reduction in the individual measurement process and exclude superpositions of macroscopically distinguishable states. The enormous experimental progress taking place in the precision of atomic physics should lead us to expect that in a few years we will have definitive experiments about these proposed nonlinear modifications of quantum theory and there is no doubt in my mind what the result of such experiments will be.

This impossibility to predict the individual event in the sense that it is not possible, not even in principle, to arrive at an accurate and detailed prediction and description of the particular process resulting in a particular event appears already very early in the course of the development of quantum mechanics. It was soon elevated to a fundamental principle in the very sense that the purely statistical nature of quantum mechanical predictions is generally accepted. With reference to the history of science, this is an extraordinary achievement, since only with Bell's theorem did it become possible to exclude in principle a more detailed description, which in order to be in reasonable agreement with common sense of course has to be local . Such a description would at least have been thinkable before. The general attitude of the majority of physicists at that time, though, was that a more detailed description, though it may be interesting, could not be verified and the question whether such a description exists or not was therefore similarly irrelevant as, according to Pauli, the old question how many angels fit onto the tip of a needle.

I propose that this impossibility to describe the random individual process within quantum mechanics in a complete way is a fundamental limitation of the program of modern science to arrive at a description of the world in every detail. In other words, I propose that this is evidence of an element in the description of nature which escapes rational dissection in detail into constituent parts.

It is remarkable that the problems associated with the individual process in quantum mechanics have found almost no entry into the *Weltanschauung* of physicists. In general, the impossibility of describing the individual process is accepted just as a consequence of the quantum rules and as a limitation of the classical possibility to describe the world. Yet, there are interesting and notable exceptions. Firstly, Pauli, from whose letter (October 13, 1951) to Markus Fierz I am quoting[22]:

"Das physikalisch Einmalige ist vom Beobachter nicht mehr abtrennbar - und geht der Physik deshalb durch die Maschen ihres Netzes. Der Einzelfall ist occasio und nicht causa. Ich bin geneigt, in dieser "occasio" - die den Beobachter und die von ihm getroffene Wahl der Versuchsanordnung mit einschließt - eine "revenue" der in dem 17. Jahrhundert abgedrängten anima mundi (natürlich in "verwandelter Gestalt") zu erblicken. La donna é mobile - auch die anima mundi und die occasio."

So, according to Pauli, a limitation to physics appears as a characteristic of the world in the not fully describable individual process. It is remarkable that Pauli sees this as the expression of an *anima mundi*. It is save to say that such a position is at variance with the way the great majority of physicists today view the problem.

It is instructive to analyze the situation from Bohr's complementarity viewpoint. According to the Copenhagen interpretation it is neither possible nor reasonable to search for properties of a quantum system as such. Since we can only communicate what we have found by using our classical language, questions concerning properties of systems only make sense, strictly speaking, as questions about classical properties of a classical apparatus. So, even here there is a fundamental border to the experience of reality, clearly a limitation to a complete knowledge of the world. This is interpreted by Wheeler[23] such that he interprets the individual process in quantum mechanics - the quantum phenomenon - as an elementary act of creation.

In an application of Bohr's statement which says that a quantum phenomenon comprises both the quantum system and the measuring device, Wheeler states that we as observers are free to decide in which way we will bring a quantum phenomenon to its close. We decide, by choosing the measuring device, which phenomenon can become reality and which one cannot. Wheeler explicates this by example of the well-known case of a quasar, of which we can see two pictures through the gravity lens action of a galaxy that lies between the quasar and ourselves. By choosing which instrument to use for observing the light coming from that quasar, we can decide here and now whether the quantum phenomenon in which the photons take part is interference of amplitudes passing on both sides of the galaxy or whether we determine the path the photon took on one or the other side of the galaxy. In both cases the individual process again contains an element that cannot be controlled. For example if we decide to measure the path of the photon - to let the path become reality - we have no influence on which of the two possible paths of the photon actually will be observed.

This is the reason why Wheeler labels the individual quantum phenomenon an elementary act of creation. We as observers play a significant role in this process since we can decide by choosing the measuring device which quantum phenomenon is realized. Still, we cannot influence the specific value obtained through the measurement. Finally, since we are part of the universe, the universe, according to Wheeler, creates itself by observing itself through us.

A very interesting and closely related position is taken by Just[24] from a psychoanalytic viewpoint. He compares the spontaneous and discontinuous reduction of the wave function in the quantum mechanical measuring process with the process of spontaneous realization ("Aha-Erlebnis"), to which in his opinion exactly the same characteristics apply.

We have now gradually brought the role of the observer into the center of our discussion, a role which is expressed by Clauser in his joint analysis with Shimony of the present EPR-Bell situation as follows[25]: "perhaps an unheard tree falling in the forest makes no sound after all". On that question there were important differences of conception between Bohr, Heisenberg, Pauli and, of course, Einstein: An apparently particularly interesting discussion took place between Bohr and Pauli in the fifties concerning the question of the so-called "detached" observer in quantum mechanics[26]. We may quote again from a letter (Feb. 15, 1955) by Pauli to Bohr[27] "... Es erscheint mir durchaus angebracht, die konzeptive Beschreibung der Natur in der klassischen Physik, die Einstein so emphatisch beibehalten möchte, das Ideal des losgelösten Beobachters zu nennen. In drastischen Worten hat der Beobachter nach diesem Ideal gänzlich in diskreter Weise als versteckter Zuschauer (spectator) aufzuscheinen, niemals als Handelnder (actor), die Natur wird dabei in ihrem vorbestimmten Lauf der Ereignisse allein gelassen, unabhängig davon, auf welche Weise die Phänomene beobachtet werden." Pauli speaks about the situation of quantum mechanics later in the same letter: "Da es erlaubt ist, die Beobachtungsinstrumente als eine Art Verlängerung der Sinnesorgane des Beobachters zu betrachten, betrachte ich die unvorhersagbare Änderung des Zustands durch eine einzelne Beobachtung - trotz des objektiven Charakters jeder Beobachtung unter gleichen Bedingungen - als eine Aufgabe der Idee der Isolation (Loslösung) des Beobachters vom Lauf der physikalischen Ereignisse außerhalb seiner selbst".[28]

Here again, a very subtle position was assumed by Bohr who writes in "Die Einheit der Wissenschaft"(The Unity of Science)[29]: "Komplementarität bedeutet in keiner Weise ein Verlassen unserer Stellung als außenstehende Beobachter, er muß vielmehr als logischer Ausdruck für unsere Situation bezüglich objektiver Beschreibung in diesem Erfahrungsbereich angesehen werden. Die Erkenntnis, daß die Wechselwirkung zwischen den Meßgeräten und den untersuchten physikalischen Systemen einen integrierenden Bestandteil der Quantenphänomene bildet, hat nicht nur eine unvermutete Begrenzung der mechanistischen Naturauffassung welche den physikalischen Objekten selbst bestimmte Eigenschaften zuschreibt, enthüllt, sondern hat uns gezwungen, bei der Ordnung der Erfahrungen dem Beobachtungsproblem besondere Aufmerksamkeit zu widmen." This is a highly refined position viewing on the one hand the observer as detached but on the other hand admitting the importance of the interaction between the measuring devices and the physical systems, where the measuring devices certainly can be chosen by the observer at will. It seems to me that the implications of that position have not yet been fully understood and appreciated.

To now turn to Heisenberg[30], we note that he sees this problem in relation to the great difficulties which, according to him, even well-known scientists like Einstein have in understanding and accepting the Copenhagen interpretation of quantum mechanics. One often notes that the roots of these difficulties lie in the Cartesian cut. That cut, according to Heisenberg, has penetrated the human soul deeply during the three centuries after Descartes, and it would take a long time before it could be replaced by a truly different position concerning the problem of reality. In my opinion Einstein's position is not represented faithfully by Heisenberg because Einstein understood Bohr's position very well and it is my impression that Einstein did not accept it just because he wanted to avoid the radical consequences it implies. I suggest that Heisenberg's position could be understood in such a way that, for him, the epistemological paradigm on which we could build a foundation of quantum mechanics has not been found yet. If this is true then quantum mechanics, which undoubtedly is correct as it supplies correct predictions, hangs in the air quasi in a state of suspense as far as its paradigmatic foundation is concerned.

Evelyn Fox-Keller[31] has claimed, as another hint at the lack of such a paradigm, that there exists a cognitive repression of the interpretation problem by the majority of physicists. For that majority the questions concerning the meaning of quantum mechanics are answered once and for all by the Copenhagen interpretation, and all further inquiry is rejected as a sign that the inquirer does not understand the topic. Further questions are called "only philosophical" and thus not befitting a physicist. But if one inquires in depth what the Copenhagen interpretation says one gets a variety of different answers. According to Fox-Keller this, too, is a sign for evasion, whereby what is evaded is the necessity of a new cognitive structure which differs radically from the existing one. Fox-Keller calls the old structure *classical objectivism*. To her, the confusion concerning the interpretation of quantum mechanics exists, thus, in the attempt to retain one or more components of the classical position. While this may be as it is; I suggest that the search for interpretations different from the Copenhagen interpretation very often is motivated by trying to evade its radical consequences, that is, an act of cognitive repression on the part of the proposers.

If following the quotes by Pauli and Heisenberg we accept that there might be a problem of proper philosophical foundation in quantum mechanics, the question arises as to what the new paradigm should look like, what its features should be. Here, it is certainly helpful to investigate which features differentiate the new theory from the old one. Of course, the quantum of action is the first to catch the eye, especially the fact that there is a universal smallest action which can be exchanged in a physical process. I propose that this fact, which originates from experiment and which is integrated in theory, should actually follow from the new paradigm. Whether the exact numerical value of the quantum of action can or must follow from a fundamental inquiry is certainly an open question. Should this be the case, then most likely by establishing the numerical value from the dimensionless numbers which consist of different natural constants like, for example, the fine structure constant and the Planck length. While there is an ongoing quest to interpret the features of the world through an anthropic principle, requesting consistency with the existence of human observers, such endeavor can be very treacherous as I tried to express in a humorous article[32]. I personally doubt that the key for a deeper understanding lies in an explanation of the numerical value of the quantum of action itself. That is because the epistemological problems of quantum mechanics are immune against a variation of the magnitude of the quantum of action over a wide range, yet again, the fact that a quantum of action exists at all surely is significant in the quest for the new paradigm.

The second feature of quantum mechanics that should be helpful in this quest is the manner in which we calculate in quantum mechanics the probability for a process to happen. Instead of simply adding the probabilities of the different ways in which a process may happen the physicist adds the complex roots of those probabilities, the probability amplitudes, a procedure for which there are precisely defined rules. An important point here is that this method can only be applied when the experimental arrangement is such that the different ways in which the process can happen cannot be distinguished, not even in principle[33]. If on the other hand the arrangement should be such that these different ways can be distinguished, the probabilities themselves are always to be added.

Two significant characteristics appear in that discussion. Firstly, we again see a role of the observer in a very fundamental way. He is free to decide through the choice of the experimental arrangement whether or not certain ways through which a process can proceed are distinguishable or not. Secondly, the formalism is such that, whenever such indistinguishable ways are present experimentally, the impossibility to distinguish is also present in the formalism. This feature is surely more adequate than the situation in classical physics where we can always mentally split the ensemble into its constituents and where the stochastic behavior of the whole ensemble follows from the behavior of its individual constituents which can be thought of as being defined to any precision. In classical physics, this can be done even in situations where we have no way to really distinguish the individual constituents and their behavior. In contrast, the quantum mechanical rule says in a colloquial form: "Thou shalt not even think of distinguishing the indistinguishable". What is really fascinating is that from the manner in which quantum physics handles the distinguishability-indistinguishability differentiation something new follows, namely the interference phenomenon.

Let us consider once again the impossibility of a detailed description of the individual statistical event in the sense of a fundamental unpredictability. I suggest that the fact is very important that while, by choosing the apparatus, we can define which one of two complementary quantities may manifest itself, for example, position or momentum, we have no influence on the value of the quantity. Therefore, as observers we have a qualifying but not a quantifying influence on the quantum phenomenon. The latter, the impossibility of a quantifying influence, is closely connected to the finiteness of the quantum of action. In this I see a necessary consequence of the first, the qualifying influence, in such a way that it ensures that the observer does not have total control over the phenomena in Nature. The observer can, thus, through his experimental questioning, jostle, so to speak, Nature, depending on which arrangement is chosen, to give answers to different questions that exclude each other - but for the price of not being able to exert a quantifying influence, an influence which specific result will materialize. It is my impression that such a differentiated position as just formulated is neither incompatible with Bohr's subtle arguments, as presented above, nor with Pauli's or Heisenberg's points of view. It is, therefore, suggestive to require a paradigmatic foundation of quantum mechanics to include this differentiated role of the observer.

Quantum non-locality, as it is expressed most strongly in the EPR situation, then, in my opinion is a consequence of the points just mentioned, if one grants that the quantum phenomena can extend over any distance. Consider for example the case of the spin measurement of two correlated particles. Before the measurement it is fundamentally impossible to assign any spin direction to the two particles involved. The experimentalists can then decide directly for one particle along which direction it can achieve a definite value by just orienting his measurement apparatus along that direction. Doing that he also defines the reality of the spin for the other particle, if we accept the Einstein-Podolsky-Rosen definition of an element of reality[34]. Yet we note again that the observer has no influence on whether the spin will be found to be parallel or antiparallel to the direction chosen. That is, again, he has no quantifying influence on Nature.

It is very highly likely that the new paradigm will contain holistic aspects. This follows in the most direct way from the fact, that in the Copenhagen interpretation it is impossible to dissect a quantum phenomenon into its parts. This may be expressed by saying that the preparation of a quantum system, its evolution and its observation, form one whole entity which, following both Bohr and Wheeler, we call the quantum phenomenon. Holistic aspects also follow from the fact that in a multi-particle-system it is not possible, not even for perfect correlations, to pre-assign properties to the individual members of the ensembles[35]. Such properties can only be assigned in the specific context of the whole experimental setup for all particles together. Then, in any case, they show up only in the correlations. This, I suggest, is another beautiful corroboration of Bohr's point of view[36].

I have purposely not dealt with questions like: Is there a border between micro- and macro physics? Is a new form of logic necessary for quantum processes? Has one's awareness an active, dynamic influence on the wave function? Such or similar positions were proposed by several physicists, but in my opinion they would all fall victim to Occam's razor: Entia non sunt multiplicanda praeter necessitatem. It is the beauty of the Copenhagen interpretation that it operates with a minimal set of entities and concepts. Furthermore, any position that would necessitate a change of the quantum formalism[37] in the sense that it leads to a change of its predictions in may opinion is, at the least, highly improbable in view of the excellent agreement of methods of experiments with theoretical prediction.

It should be noted that there actually could be a tension between the excellent agreement of quantum mechanics with all experiments and the search for a new paradigmatic foundation of the theory. This has most clearly been formulated by Rabi[38]:"The problem is that the theory is too strong, too compelling. I feel we are missing a basic point. The next generation, as soon as they will have found that point, will knock on their heads and say: How could they have missed that?".

Finally, a quote from Einstein's letter to Schrödinger of January 22, 1950. "Es ist einigermaßen hart, zu sehen, daß wir uns immer noch im Stadium der Wickelkinder befinden und es ist nicht verwunderlich, daß sich die Kerle dagegen sträuben, es zuzugeben (auch sich selbst)."[39] Still today there seems to be some truth in that statement, even though I, as hopefully became clear from my above explications, can neither share Einstein's nor Schrödinger's opinions with respect to the interpretation of quantum mechanics. Yet it is very much to their credit that they both clearly understood which radical changes in our view of the world (*Weltanschauung*) quantum mechanics in the end necessitates. Changes which might be so radical that it is certainly reasonable and understandable to thoroughly investigate all other possibilities before taking the leap. To my knowledge the most radical position with respect to that leap was assumed by Pauli as I tried to explicate above and it might very well be that someday we will follow his guidance. Yet it is also highly recommended to follow the guidance of the Copenhagen interpretation, that is, not to make any unnecessary assumptions not supported by a thorough analysis of what it really means to make an experiment.

This paper is dedicated to Prof. K.V. Laurikainen at the occasion of his 80th birthday. I would like to thank him very much for bringing the attention of the physics community to Pauli's rather unconventional thinking and personally I thank him for making much of this work available to me before publication.

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While I leave the question open in the present paper which interpretation should be preferred, I don't hesitate to declare my preference for the Copenhagen interpretation.

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"That which is physically unique cannot be separated from the observer anymore - and therefore falls through the net of physics. The individual case is occasio and not causa. I am inclined to see in this "occasio" - which includes the observer and his choice of the experimental setup and procedure - a "revenue" of the "anima mundi" (of course in "changed shape") that was pushed aside in the 17th century. La donna é mobile - also the anima mundi and the occasio."

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"To me it seems quite adequate to call the conceptual description of nature in classical physics, which Einstein wants to keep so emphatically, the ideal of the detached observer. In drastic words the spectator must, according to this ideal, appear in a fully discrete manner as a hidden spectator. He can never appear as an actor. Nature is hereby left alone in its predetermined course of events, without regard to the manner in which the phenomena are observed."

[28]

"Since we can regard the measuring instruments as a kind of extension of the observer's sensory organs, I see the unpredictable change of the state through the individual observation - in spite of the objective character of every observation under the same circumstances - as a rejection of the idea of the detachment of the observer from the course of physical events outside of himself."

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"Complementarity means in no way an abandonment of our position as detached observers. It should, on the contrary, be seen as a logical expression of our situation concerning objective description in this area of experience. The realization that the interaction between measuring devices and the physical systems forms an integrating part of quantum phenomena, has not only revealed an unexpected limitation of the mechanistic view of nature which attributes well defined properties to the objects themselves, but it has forced us to give special attention to the problem of observation when ordering the experiences."

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"It is quite hard to accept that we still are in the stage of babies in their diapers, and it is not surprising that the fellows are unwilling to admit this (even to themselves)."

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U. Ketvel et al. (Eds.), Helsinki University Press, 1996.
