Various interpretations of quantum mechanics

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Abstract

Brief review of various interpretations of quantum mechanics is presented. Special consideration is given to the problem of measurements and collapse of wave function.

Large success of quantum mechanics in explanation of a large part of physical phenomena leaves not enough place for doubts in its regularity. Starting from the beginning of this century, quantum mechanics never came in a conflict with the results of experiments and could make a huge number of predictions.

Nevertheless, we should not forget about many fundamental problems, which arose already at the early stages of development of the theory. At that time the debates about these problems rendered large influence on the formation of quantum mechanics. But then the discussion moved to philosophical circles and has ceased to raise noticeable interest in physical circles. Among the physicists the belief in the so-called Copenhagen or orthodox interpretation of quantum mechanics was ratified. This interpretation is connected, first of all, with the name of Bohr. Heisenberg, Dirac, Born and a majority of other founders of quantum mechanics who were supporters of this interpretation. Close position was shared by von Neumann.

At the same time, actively working physicists did not usually go deep into arguing about the basis of quantum mechanics. Instead the basic statements of the orthodox approach were frequently used as recipes. Two facts promoted that. First, these recipes worked very well. Second, many basic statements were formulated in the form of series of principles: the principle of complementarity, the principle of indeterminicity, the projective principle. From the very beginning the physical content of these principles was not cleared up, and it was offered to accept them in the form of a set of dogmas.

However, since the sixtieth years, an interest to discussing the basis of quantum mechanics revives among physicists. An attempts, although not so successful, are undertaken to develop an alternative approaches to quantum mechanics. In particular, various variants of the so-called ensemble approach begin to develop rather actively. Its supporters usually begin their genealogy from Einstein.

Kemble, Popper and Langevin were its supporters at the early stages of development of this approach. In later time Everett, Ballentine, Bohm, Lande, Blokhintsev and many other worked in this direction.

The first separation of physicists into two large groups took place in connection with the problem of completeness of quantum mechanics as the physical theory. Bohr and other supporters of the orthodox direction stated that quantum mechanics gives complete description of an individual physical object, as complete as it is possible. On the contrary, Einstein always thought that quantum mechanics is a correct and complete statistical theory of ensembles, but not the theory of individual physical objects. Personally to me such point of view seems more convincing. Of course, the supporters of ensemble direction agree with Einstein.

The supporters of different directions differently estimate the role of wave function in quantum mechanics. In the orthodox interpretation the wave function is considered as an attribute of an individual quantum object, in the ensemble interpretation it is considered as a characteristic of an ensemble of identically prepared quantum systems.

The second point, on which there are the essential disagreements, is a problem of causality. In the orthodox interpretation the causeless phenomena are supposed. Most precisely, this position is formulated in the famous book of von Neumann [1] about mathematical bases of quantum mechanics: " there is no experiment, which would support the presence of causality, since the macroscopic experiments are in principle unsuitable for this purpose and quantum mechanics, the only theory which is compatible with the set of our experimental knowledge about elementary processes, contradicts it".

However, such radical refusal from the principle of causality did not satisfy earlier and still does not satisfy now many physicists. For example, without the principle of causality it is very complicated, if possible at all to solve the famous Einstein-Podolsky-Rosen paradox [2]. The solution of this problem, proposed by Bohr, does not seem to be very convincing. And apart from the Bohr solution a number of other variants were proposed within the framework of the orthodox interpretation. A large number of different variants indicates that none of them can satisfy majority of physicists. On the other hand, acceptance of the principle of causality allows to avoid this paradox.

In most variants of the ensemble approach the principle of causality is taken in the hard form. It is assumed, that there is some physical reality, which univalently determines the behaviour of any object. Though, for example, Blokhintsev adheres to other approach. He understands the causality as some statistical regularity. Here his approach is not too different from the orthodox one.

One of the most popular ways of introduction of a causality to quantum mechanics is the idea of hidden parameters, which claims that the state of an individual physical system is determined not only by the wave function, but also by some set of parameters, which are not taken into account in the apparatus of quantum mechanics.

Introduction of hidden parameters makes many results of quantum mechanics easily interpretable, allows to solve series of paradoxes, which arise in the orthodox approach. However, as von Neumann [1] showed, the idea of hidden parameters contradicts the mathematical structure of the theory, accepted in quantum mechanics for the description of observables and states.

In fact, Bell [3] showed, that in his proof von Neumann made the assumptions which are too restrictive. They are really true for the standard apparatus of quantum mechanics, but in some of its modifications, in particular in the model proposed by Bohm, these assumptions are not fulfilled. Therefore the program of hidden parameters cannot be considered as finally closed.

However simultaneously with partial rehabilitation of the hidden parameters Bell has deduced the famous inequalities, which should be fulfilled in models with the hidden parameters. These inequalities have two remarkable properties. First, within the framework of standard quantum mechanics it is easy to specify a situation, when these inequalities are broken. Second, the inequalities can be checked experimentally. Apparently, these checks show, that the inequalities can be broken. True, the very persistent skeptics until now try to state that the complete experimental proof of this fact is absent. But general scientific opinion is not on their side.

Among the modern supporters of the ensemble-causal approach in quantum mechanics the so-called PIV-model is popular. This model is described rather explicitly in the recently published review of Home and Whitaker [4]. In this review the common comparative analysis of the orthodox and ensemble approaches is given.

The basic idea of the PIV-model consists in the assumption, that each physical system, being a member of quantum-mechanical ensemble, has the " pre-assigned initial values " for all dynamical variables. On the one hand, these values distinguish different members of one ensemble. On the other hand, a part of these initial hidden values are made explicit by really performed measurements. The PIV-model has a lot of likenesses with the hidden parameters model. The PIV-model allows to solve quantum-mechanical paradoxes rather simply, but as far as I know, the problem of the Bell inequality is not solved in it.

Perhaps it is most difficult to believe in the statement, which is done in the orthodox quantum mechanics about the collapse of a vector of state. In the elementary form this statement is reduced to the following. The state of a quantum-mechanical system is described by a vector of state $|\psi\rangle$. If definite basis is chosen in the space of states , this state can be described by the wave function ψ. By quantum-mechanical interactions the vector of state (the wave function) evolves in time, obeying the equation of motion, for example the Schrödinger equation. In this case the causality is observed in a complete volume. However such serene evolution is interrupted at a contact of the quantum object with a classical measuring device.

Let this measuring device to measure an observable Q, which in the apparatus of quantum mechanics, an operator $\hat{Q}$ corresponds to. Let u_i to be the eigenfunctions of the operator $\hat{Q}$ with eigenvalues Q_i

$$\hat{Q}u_i = Q_i u_i. \tag{1}$$

Then in the measuring device, first,happens the expansion of the wave function ψ

$$\psi = \sum_i c_i u_i \qquad c_i - \text{numbers}, \qquad \sum_i |c_i|^2 = 1, \tag{2}$$

second, with the probability $|c_k|^2$ the wave function ψ transforms into one of the functions u_k

$$\psi \rightarrow u_k. \tag{3}$$

The transition (3) is just a collapse of wave function. This transition is purely probabilistic, the causal evolution is interrupted in it.

The statement about the collapse is formulated more accurately, if the statistical operator (density matrix) $\hat{\rho}$ is used instead of vectors of state. I shall remind, that to each pair of (normalized) vectors of state $|\xi\rangle$, $|\eta\rangle$ there corresponds an operator

$$\hat{\rho}(\xi,\eta) \equiv |\xi\rangle\langle\eta|. \tag{4}$$

The operator $\hat{\rho}(\xi,\xi)$ is a projector onto the state $|\xi\rangle$. Formulated by von Neumann in terms of operators $\hat{\rho}$ the statement about a collapse of wave functions looks as follows:

$$\hat{\rho}_I = |\psi\rangle\langle\psi| \equiv \sum_{i,j} c_i c_j^* |u_i\rangle\langle u_j| \;\to\; \hat{\rho}_F = \sum_k |c_k|^2 |u_k\rangle\langle u_k|. \tag{5}$$

The operators $\hat{\rho}_I$ and $\hat{\rho}_F$ describe a state of a quantum system before and after measurement, respectively. The operator $\hat{\rho}_I$ is the projector, in the sum over i and j to the left of the arrow non-diagonal $(i \neq j)$ terms are present, therefore the corresponding state is pure. The operator $\hat{\rho}_F$ is equal to the sum of projectors, such state is mixed, in the sum to the right of the arrow the non-diagonal terms are absent. The transition from $\hat{\rho}_I$ to $\hat{\rho}_F$ is referred to as a projective principle.

In the following the statement (5) was improved by taking into account the state of the measuring device

$$\hat{\rho}_I \otimes \hat{\sigma}_I^A \;\to\; \sum_{i,j} c_i c_j^* |u_i\rangle\langle u_j| \otimes |W_i\rangle\langle W_j| \;\to\; \sum_k |c_k|^2 |u_k\rangle\langle u_k| \otimes \hat{\sigma}^A_{F(k)}. \tag{6}$$

Here $\hat{\sigma}_I^A = \sum_{i,j} |W_i^I\rangle\langle W_j^I|$ is the statistical operator of the initial state of the device, and $\hat{\sigma}_F^A(k) = |W_k^I\rangle\langle W_k^I|$ is the statistical operator of the final state of the device. This state corresponds to the instrument reading F_k.

If the collapse is considered as a physical process, it looks very strange. First, it breaks the principle of causality, second, it contradicts the relativity theory. It is seen easier from the elementary form of representation of the collapse by the formulas (3). The wave function ψ is spreaded over the space. As a result of transition (3) it turns instantly (very quickly) to a wave function u_k. One can create such conditions of the experiment in which the modification of wave function must be spreaded with a superlight velocity if we want to describe the results with the help of the collapse.

By the way, many modern physicists concern quite seriously a possibility to use a collapse for transmission of information with superlight velocity. The whole series of papers, published recently in UFN (see, for example [5]) is devoted to this problem. I consider such possibility as fantastic.

The orthodox quantum mechanics does not give anobvious physical mechanism of realization of the collapse. Fuzzy reasonings on the influence of a classical device and observer on a quantum object are usually adduced. As usual, the most definite judgments can be found in the von Neumann's book [1]. He proposes to consider the process of measurement as some chain, which connects processes objectively flowing in nature with some " interior I " of the observer. Links of this chain are separate parts of the measuring device and parts of human body, ensuring process perceptions. In all these links the physical processes happen, obeying the principle of causality, but at some stage the physical reality transits by jump in mental perception. The causality is broken in such jump. We can move the jump along the chain at own discretion, but it necessarily should be somewhere.

Despite the whole ingenuity of these reasonings, they do not seem especially convincing. Besides, the interpretation of such toy situations as "Schródingers's cat" or "Wigner's friends" are very difficult from such positions.

Of course, the attempts of interpretation of the collapse of wave function in purely physical terms were undertaken not once. There existed a popular explanation of the collapse by the influence on a quantum object of irreversible processes, which happen in the measuring equipment during the measurement. The supporter of such point of view was Rosenfeld. However it is very inconvenient to explain the collapse from such positions in the case of so-called negative experiment. In this experiment we conclude about properties of the quantum object not by means of registration of passing of this object through the device, but by means of registration of a lack of such passage. In this case the device should not influence the quantum object.

From my point of view, the scheme of description of the wave function collapse, developed recently by Namiki merits attention. This scheme is described in the review by Namiki and Pascazio [6] which is devoted to modern aspects of the quantum theory of measurements. Namiki considers the collapse not as a result of vanishing of any part of wave function, but as a loss of coherence of various parts.

Schematically Namiki reasonings may be presented as follows. At the first stage (in the analyzer) the wave function ψ of the quantum object is decomposed in components u_i (the formula (2)) in the measuring device. At the second stage the detectors, included in the structure of measuring device, act on components u_i, chaotically changing their phase. Such deformed wave functions generates statistical operator described by the left-hand side of the formula (5)

$$\hat{\rho}_I = |\psi\rangle\langle\psi| \equiv \sum_{i,j} c_i c_j^* |u_i\rangle\langle u_j|, \tag{5'}$$

in which factors c_i, c_j^* are gained with additional phases, depending on the number of the experiment. If after that we shall average the relation (5′) over many experiments, the non-diagonal elements are mutually compensated by randomnesses of phases, and the right-hand side of (5′) will pass into the right-hand side of (5):

$$\hat{\rho}_F = \sum_k |c_k|^2 |u_k\rangle\langle u_k|.$$

Similar reasonings are carried out in the approach (see, for example [7]) in which the assumption about collapse is substituted by the assumption about orthogonality of various states of the measuring device. Such scheme of reasonings is used in this approach. The average of many experiments can be described mathematically by evaluations of partial trace over the states of the device in the middle part of the formula (6)

$$\sum_{i,j} c_i c_j^* |u_i\rangle\langle u_j| \otimes |W_i\rangle\langle W_j|. \tag{6'}$$

Due to orthogonality the trace of the non-diagonal operator $|W_i\rangle\langle W_j| \quad (i \neq j)$ is equal to zero, therefore the non-diagonal terms drop out in the formula (6′) and it will pass into the right-hand side of formula (6).

However, as Namiki explains in his review, such vanishing of the non-diagonal terms is not equivalent to the collapse of wave function, since the coherence between various parts of the wave function is not broken. Therefore, if we shall put a synthesizer behind the detector, various parts of wave function will be coherently united in it. It should not happen at the collapse.

Now I shall pass to the account of my version of the interpretation of quantum mechanics. The basic ideas of the version are published in the papers [8, 9, 10]. However, essentially modified variant will be explained here.

We shall assume that there is a complicated system of oscillations in the vacuum and they form a wave field. There are local structurless singularities in the field. The quantum-mechanical elementary particle corresponds to each of these singularities. This particle consists of the singularity (nucleus of the particle) and the regular part of the wave field, which is coherent to the nucleus of the particle. This part of the wave field forms the shell of the particle.

The nucleus is a carrier of all observables, connected with the particle. These observables are stored in the latent form in the nucleus. The latter means that not definite numerical magnitudes but the elements of some noncommutative algebra correspond to the observables. A part of these observables can pass from the latent form into explicit one, when the particle interacts with an approaching measuring device. It is supposed that the concrete result of a measurement depends on the state of the shell.

We shall assume that the state of the shell is unique for each particle. For example, it is possible to assume that the state of the shell depends on the whole previous history of the particle, i.e. the shell is memory, which stores an information about a history of the particle. In this case the unrecurrence of the state of the shell is easily explained by uniqueness of the history of each particle. One can find another consideration of histories in [11].

Uniqueness of the state of each shell allows to reconcile two seemingly irreconcilable concepts — probability interpretation of quantum mechanics and hard determinism. Really, on the one hand, it is possible to think that the behaviour of each individual particle is univalently determined by its shell and the state of the environment. It is stacked into the scheme of hard determinism. On the other hand, in a general case, the prediction for the behaviour of an individual particle can be only probabilistic, as any prediction is done on the basis of the previous experience. We fix, that definite consequences follow from definite set of initial conditions (causes). However, it is impossible univalently to predict consequences if this set of causes is never repeated. At best, we can make a probabilistic prediction if it is possible to reveal some repeated subset of the causes.

Moreover, the state of shell cannot play a role of a hidden parameter, with the help of which the behaviour of the particle can be classified further, because each such class always consists of one element. In such situation a trivial statement is only possible: " the particle behaves, as it behaves ".

Thus, the corpuscular - wave dualism of quantum mechanics has the quite obvious interpretation in the model proposed. The structurless local nucleus is a valent component of quantum particle, coherent oscillations of the nucleus and shell (extended in space) form wave information field of the particle. The information stored in this field determines a kind of mapping of the latent values of observables in the explicit values.

Collective oscillations of nuclei are possible in a complex, consisting of several particles. The vacuum oscillations , which are coherent to these collective oscillations, form an information field of the complex. This field plays the role of multiparticle memory. The values of every possible correlation magnitudes are determined by a state of the multiparticle information field.

The quantum object can undergo a real physical action, which changes the information in its memory, but which is not described by quantum-mechanical equations of motion. Such modification of wave function is natural to define as an active or objective collapse.

For an illustration of this phenomenon we shall discuss an experiment, the scheme of which is represented in Figure 1. The device consists of four mirrors (1,2,3,4) and three detectors (D_1, D_2, D_3). The mirrors 1 and 4 are semipermeable. The detectors D_1 and D_3 are switched on coincidence, and the detector D_2 is switched on anticoincidence. Through the detector D_1 the photons are started into the device. The detectors D_1 and D_3 are necessary only for registration of photons. The detector D_2 plays central role in the phenomenon of collapse. At the device the photons either are reflected from mirrors, or pass through them. After reflection from the mirrors the phase of oscillations changes by $\pi/2$, at passage through a semipermeable mirror the phase does not change. The mirror 1 plays the role of the analyzer, in it the initial beam of photons is divided into two branches: 1-2-4 and 1-3-4. The mirror 4 plays two roles: the synthesizer and the second analyzer.

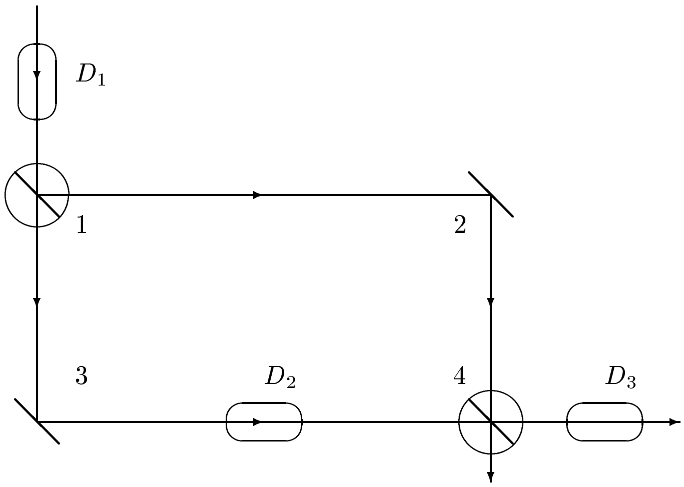

Figure 1.

We shall at first consider a variant of the experiment, when the detector D_2 is switched off (or is absent). Elementary calculation of modification of phases of the oscillations in the mirrors shows that due to interference the photons will not hit the detector D_3. Since the detectors D_1 and D_3 are switched on in coincidence, the device will not register any positive result.

We shall now consider a variant of the experiment, when the detector D_2 is switched on. Since the detector D_2 is switched on in anticoincidence, only those events, when the photon does not pass through the detector D_2, are taken into account in the experiment. Therefore the interferences will be absent in the mirror 4 and about half of the photons will hit the detector D_3. The result of the experiment will be positive. This result completely agrees with the orthodox interpretation — due to a collapse the branch 1-2-4 of the wave function is destroyed.

In the Namiki interpretation this result is explained too. The branch 1-2-4 is not destroyed, but its phase moves chaotically with respect to phases of the branch 1-3-4. Therefore the interference effect disappears in the averaging over a number of events.

However now the experimental technique of the weak beams has increased, so that experiments with separate photons are possible. They allow to check the presence of an interference (detector D_2 is switched off), when there is one photon in the device. The expected result of the experiment is univalent (lack of a signal in the detector D_3) therefore averaging over a number of events is not required. The experiments with a similar scheme of measuring device were fulfilled really [12], the interference was observed.

In the variant of the experiment when the detector D_2 is switched on, the positive result should be observed in about a half of cases, therefore the averaging over a number of events is not required too. As a result, the given experiment is difficult to interpret in the Namiki scheme. Besides, the events when the photons do not hit the detector D_2, are automatically selected in this experiment, therefore the random displacement of phases does not happen.

We shall now look if it is possible to interpret the results of the given experiment using a composite model of quantum objects, which is offered by me. In this model each quantum particle consists of two constituents: dynamical (nucleus) and information (wave field) components. It is possible to assume, that the quantum object participates in interactions of two types: dynamical and information ones. The dynamical interaction goes with participation of a nucleus and results in a modification of dynamical characteristics of an object. The information interaction can happen without participation of a nucleus and, practically, without a modification of dynamical characteristics. For example, only the phases of oscillations change in the wave field.

We shall suppose, that the information connection is strong inside a quantum object. So, if the phases of oscillations change in some region of the information field, this modification is quickly spreaded to the whole information field and the coherence of separate sections of this field is kept. However it will not happen if the sections are isolated from each other.

We shall return now to discussing the experiment. We shall at first consider a case, when the detector D_2 is switched off. The mirror 1 plays a role of the analyzer and has two properties. First, the shell of the photon is divided in two parts, which are then spreaded into two routes 1-2-4 and 1-3-4. The coherence of both parts is kept. Second, the mirror 1 is a point of a bifurcation for the nucleus of a photon. It signifies, that dynamically both routes are admissible for the nucleus. However due to information, stored in the shell, a choice of the route will be made univalently. But from the point of view of quantum mechanics this choice will be random. The fact is that the quantum mechanics deals not with information field, but only with its generalized performance — wave function. The various configurations of the information field correspond to the same wave function. On the other hand, with the help of preliminary measurements we can receive an information only about wave functions, therefore the choice by the nucleus of one of the routes will be random for us. Effectively the information connection between the nucleus and the shell plays the role of random dynamical force in the point of bifurcation.

The phases of oscillations of the nucleus and separate sections of the information field can vary when they go on both routes, but the coherence of all components of the photon is kept. Therefore coherent synthesis (interference) of all constituents of the information field is possible in the mirror 4. Due to this interference the information field will not be spreaded towards the detector D_3. Therefore the probability for the nucleus to hit the detector D_3 will be equal to zero.

We shall now consider the second variant of the experiment, when the detector D_2 is switched on. In the mirror 1 everything will happen in the same way as in the first variant. Two scenarios are further possible, in which the nucleus will go by the route 1-3-4, or will go by the route 1-2-4. In the scenarios with the route 1-3-4 the nucleus hits the detector D_2. There the quantum object participates in dynamical and information interaction with the classical device. The device goes out of unstable equilibrium due to dynamical interaction with the nucleus. The catastrophic process develops in the device. This process has macroscopically observable result and the quantum object is registered.

Due to information interaction of the quantum object with the detector the character of oscillations of the nucleus and that part of the shell which goes on route 1-3-4 changes. Since these components of quantum object strongly interact informationally among themselves, their coherence is kept. But the part of the shell, which goes by the route 1-2-4 appears to be isolated from this interaction. As a result, the wave field in the channel 1-2-4 loses coherence with the field in the channel 1-3-4. Since only the field which is coherent with nucleus is a part of quantum particle, the wave field of the channel 1-2-4 vanishes for the quantum object. Effectively the part of information, stored in the memory of the quantum object, is lost. This process of forgetting is irreversible.

This process results in a sharp modification of the information field of the quantum object. The wave function of the object also changes sharply thereof. This phenomenon has all features of the objective (active) collapse. In spite of the fact that the wave function changes almost instantly in a large volume, any inconsistency with a relativity theory does not arise. However, it is no more an element of the structure of the object. The modifications happens in the channel 1-3-4, i.e. the quantum object change. Thus, the wave fields in the channels 1-2-4 and 1-3-4 do not disappear in the collapse, but these fields lose the coherence with each other. Therefore in the mirror 4 interferences will be absent.

We shall now address the second scenario, in which the nucleus goes by the route 1-2-4, and the nucleus-free wave field goes through the detector D_2. This field does not interact dynamically with the detector. In this case the cause, generating catastrophic process in the detector is absent. Any macroscopicaly observable of the reaction of the device will not be present.

However the information interaction between the detector and the wave field is available. This interaction will have no effect on behaviour of the detector, as it consists of huge number of incoherent microobjects. The additional random displacement of phases of oscillations will not change anything.

On the contrary, the information action of the detector will affect strongly the wave field in the channel 1-3-4. This field will lose coherence with the field and nucleus in the channel 1-2-4. The situation will be the same as in the first scenario. Thus the collapse develops in negative experiment in the same way as in the positive one.

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