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RESEARCH ARTICLE

PHILOSOPHICAL ANALYSIS FOR COPENHAGEN INTERPRETATION OF QUANTUM MECHANICS.

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Abstract

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Copenhagen interpretation, as the orthodox interpretation of quantum mechanics currently, bases on Mach's positivistic philosophy. It takes the Max Born's statistical interpretation of wave function, the Weiner Heisenberg's uncertainty principle, and the Niels Bohr's principle of complementarity as the heart. This paper aims to analyze the Copenhagen interpretations for the properties and evolutions of quantum objects from the viewpoint of determinism, realism, and epistemology.

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Introduction:-

With the developments of science and technology, the concept and application of"quantum"have penetrated the ins and outs of our lives. The rise and rapid growth of quantum key distribution and quantum teleportation, quantum medical, quantum computer, quantum life, and so on, indicate that our life have enter a quantum era. Without any doubt, quantum mechanics, as the theoretical foundation of quantum technology, displays bright developments and applications. Quantum theory, with unique formats and specific algorithmic rules, effectively explains and predicts the phenomena of micro-worlds. However, quantum theory has so far been a set of disputable theory and continually readjusted by new concepts. The differences in the disputations consist in the understanding of the quantum concepts, i.e. a realistic supports for quantum mechanics.

It is well known that the classical mechanics bases on both experimental and mathematical methods. The former plays the role of discovery and test for the theory, while the later is the most favorite and effective tool in describing and understanding the worlds. The physical concept dominates the mathematical description, while the latter is just a more accurate auxiliary. The materiality, activity, and perceptibility of experiments, combined with the logicality, reasoning, and systematism of mathematical methods, establish the realistic standpoint of classical physics, i.e. from Newton's mechanical realism to Einstein's objectivist realism [1]. The philosophy of classical physics, i.e. classical realism, can be come down to four fundamental hypotheses, which leads to physicalism, i.e. the view that everything including minds and consciousness can be reducible to matter. (1) the existence of world is independent of humankinds and observations, and the consciousness is irrelevant to observation; (2) things are knowable — the world can be described objectively and faithfully by physical laws and theories; (3) the causality of determinism — the physical quantities represent the properties of objects and their relations are expressed by equations, we can learn the state of objects from solving the corresponding equations; (4) the principle of separability that bases on the locality and individuality of macro-particles, — if we separate two interacting particles (or systems), one of them will not be affected when measuring the other. According to the history of western philosophy, the materialistic realism follows the dialectical unification between the materialism and mentalism, and native materialism dominated the ideology in physics.

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The birth of quantum mechanics challenged the latter two and endowed the former two with new concept, which contradicts classical physics in each point [2]. Weiner Heisenberg firstly considered the time-independent quantum state and derived the commutation relation between coordinate and momentum, which became the basis of matrix mechanics and ascribed the dynamics to the evolution of observable quantities. In the meantime, Erwin Schrödinger associated the evolution of quantum system with that of wave function and established the wave mechanics, whose core is the differential equation. Von Neumann finally proved in 1932 the equivalence between the matrix mechanics and the wave mechanics, despite the different assumptions and mathematical formats, by describing the quantities in quantum mechanics as operators in Hilbert space. However, both matrix mechanics and wave mechanics are just two kinds of mathematical languages describing quantum mechanics, without any physical interpretations until M. Born put forward the statistical interpretation and probability of wave function. Accordingly, the Heisenberg's uncertainty relation was endowed with physical meaning, i.e. the coordinate and momentum of a particle cannot be measured simultaneously, which arises from the wave-particle duality of a particle. The Bohr's concept of complementarity subsequently was developed to explicate the wave-particle duality of microphysical objects. Generally speaking, the philosophical precondition of quantum theory consists both of the quantum concept and hypothesis and of the mathematical framework and experimental facts, which is intrinsic to the theory and is part of the theory. The mathematical frameworks, describing the quantum theory, have been acquired their wide applications, including the functional analysis as the foundation of Heisenberg's matrix mechanics, the differential equations as the base of Schrödinger's wave mechanics, and the Feynman path integral used to dealing with the higher-order perturbation theory. However, the interpretations for quantum theory don't belong to the theory itself, but the philosophical scope. Consequently, the interpretations for quantum mechanics depend on the faith of physicists, which causes the different factions for the concept of quantum mechanics.

In this paper, we will focus on the Copenhagen interpretation and discuss the philosophical foundations and the challenges. The paper is organized as follows. Firstly, we will review the physical concept of Copenhagen school of thought for quantum mechanics. Then, we will analyze the cores of Copenhagen interpretation by using different philosophical views. Finally, we will summarize our discussions.

Copenhagen Interpretation of Quantum Mechanics:-

The interpretation of quantum theory denotes the way that we explicate the mathematical formats, physical concepts, and philosophical foundations of the quantum problems, such as quantum probability, quantum measurement, quantum entanglement, and quantum correlation, etc. Copenhagen interpretation, which bases on the Born's statistical interpretation of wave function, takes the Bohr's complementarity principle as the core, and obeys the Heisenberg's uncertainty principle in essence, is the orthodox interpretation of quantum mechanics currently.

According to traditional philosophical sense and physical concept, we can feel the macro-objects and thus can describe their states and properties by using the classical physical concepts. However, we cannot feel the micro- or sub-atomic objects. In order to learn the information of micro-worlds and the states of quantum objects, we have to resort to a classical object, which is called as "classical apparatus" [3]. If we want to study the motion of an electron, we can shine a beam of light on it. Then, the photon, which is regarded as classical apparatus, will come into interaction with the electron, which is taken as the quantum object. Consequently, the original state of the electron is changed by the photons, because of the considerable interactions. That is to say, the state of quantum object is interfered by the classical apparatus, during the process of measurement. When we finish the measuring process, the state of both the quantum object and the classical apparatus has been altered, and both of them reduce or collapse to their eigen-states. As a result, the measured state of the electron actually represents the result of the interaction, instead of its original state before the measurement. Furthermore, the quantum object, e.g. an electron, cannot move along a definite path, but appears as wave packet, i.e. it cannot have a definite position in space. If we want to know the coordinate of the electron with more accuracy, the measurement should be confined to a very narrow region. Accordingly, more and more momentum has been transferred from the classical apparatus to the electron, because of their interactions, which remains a larger uncertainty of momentum. Therefore, the conjugated set of physical quantities describing the state of the quantum objects cannot simultaneously be measured exactly. The measured result obeys the probability statistics [4], and what make sense to quantitatively describe the state is determined by the statistical average values of measured quantities. The extent of accuracy is subject to the Heisenberg's uncertainty principle.

Born's Statistical Probability Interpretation:

On the basis of propositions of quantum mechanics, we always describe the state of a quantum object as the wave function ψ, which can be a definite function of such as coordinates $\vec{r}$, i.e. $\psi(\vec{r})$, or momentum $\vec{p}$, i.e. $\psi(\vec{p})$. In order to study the relation between wave function and particles, Max Born resorted to Schrödinger equation and investigated the quantum collision, during which it was realized that the square of amplitude of scattering waves should be treated as the probability of deflected particles in some region. According to M. Born, the square of modulus of the wave function $|\psi|^2$ represents the probability of a particle we can find in some certain space region. Actually, the wave function is a kind of probability wave, instead of the classical waves, which is just the mathematical description of probability distributions.

According to quantum formalism, the Born's statistical probability interpretation can be summarized as follows. (1) The state of a quantum object or a micro-system can be described by the wave function ψ, and the probability density for finding one or multi-particles at the configuration $\vec{r}$ is $|\psi(\vec{r})|^2$. The wave function can be regarded as the totally observable properties of quantum objects in a micro-system. The results of measurement follow the statistical probability, which can be expressed generally as $\iint \psi(\vec{r})\psi^*(\vec{r}')d\vec{r}d\vec{r}'$, and the integration is extended over all the configuration space. (2) To the extent that the results of measurement are registered configurationally, at least potentially, it follows that the results of measurement must agree with the same Schrodinger equation before the measurement. For a micro-system, the Hamiltonian is not an explicit function of the time. The wave functions ψ_1 and ψ_2 describe the states at the moments t_1 and t_2, respectively, which related to each other according to $\psi_2 = \mathrm{e}^{-\frac{\mathrm{i}}{\hbar}(\mathrm{t}_1-\mathrm{t}_2)}\psi_1$. Therefore, the state of the system ψ_2 at t_2 can be determined exclusively by the state ψ_1 at t_1. That is to say, the wave function, following the Schrödinger equation, can give us any state of the system at corresponding time, and the probable value of any state can be obtained according to the statistical probability. (3) The superposition of probability of different states is not the simple superposition of each probability. Taken the double-split experiment with electron as an example, we define the state of the electron on the screen that passes through the split "1" as ϕ_1 and that passes through the split "2" as ϕ_2. According to the principle of superposition, the possible state of electron passing through both splits simultaneously appears on the screen can be expressed as $\phi = c_1\phi_1 + c_2\phi_2$. The corresponding probability then is $|\phi|^2 = |c_1\phi_1 + c_2\phi_2|^2$, i.e. the superposition of probability amplitudes, which includes an additional interference term $c_1c_2^*\phi_1\phi_2^* + c_1^*c_2\phi_1^*\phi_2$. The additional interference term arises from the interference of the apparatus with electron, which manifests as light and dark stripes on the screen. (4) We always use the Hermitian operators to represent the corresponding observable mechanical quantities, such as coordinate, momentum, and so on. If two of Hermitian operators are commutative, they can be measured simultaneously with accuracy and have the common eigen-state. Generally speaking, the operators in quantum mechanics don't satisfy the commutation and follow the commutation relation $\hat{F}\hat{G} - \hat{G}\hat{F} = i\hbar\hat{k}$.

The essential differences of the statistical probability interpretation in quantum mechanics with the conventional probability statistics lie in the linear superposition of the quantum states. Consequently, we have to abandon the classical determinism and causality, in order to understand the quantum probability, and follow the statistics. The quantum probability, according to Weiner Heisenberg, is the statistical description for the quantum systems, and it is ascribed the statistical law to the uncertainty of the state of motion of the particles.

Heisenberg's Uncertainty Principle:

Based on the Born's statistical probability interpretation of wave function and Schrödinger's wave mechanics, W. Heisenberg proposed the uncertainty principle in 1927 and explicated the wave-particle duality of quantum objects in essence, which becomes the heart of Copenhagen interpretation and the primary and fundamental principle in explaining the nature of quantum system.

According to the uncertainty principle, we cannot measure, to a sufficient degree of accuracy, the coordinate and momentum of a particle simultaneously, and the results obey the following quantitative relation,

$$\overline{(\Delta x)^2(\Delta p)^2} \geq \frac{\hbar^2}{4},$$

which tells us that the uncertainty of measurement depends, to some extent, on the characteristic quantity on the quantum scale, i.e. the Planck constant "h" (or reduced Planck constant "$\hbar$"). It is clear that we cannot get the exact values of two canonical and conjugate dynamical variables that describing the state of a system. That is to say, when we get the exact value of one state parameter, the value of the other one cannot be measured at all, and the uncertainty of the measured result is up to infinity, and vice versa. The uncertainty principle gives us a lot of information of ground state, such as the ground-state energy, and helps us to understand many atomic phenomena, e.g. the stability of the hydrogen atom.

There is another uncertainty relation between energy and time [5], i.e.

$$\Delta E\cdot\Delta t\geq\frac{\hbar}{2}.$$

However, its implication is quite different from that of Heisenberg's uncertainty principle. In the Heisenberg's uncertainty principle, the relation involves two dynamical variables and just once-through measurement. However, we need to do twice measurements for the state of a system, when getting the energy-time uncertainty relation. We get an energy value of the system for the first-time measurement of the state and another energy when measuring the same state of the system at the second time after a time interval of Δt. Then we can find that there is an energy difference ΔE, even for the same state, and then the classical energy conservation is violated. According to the energy-time uncertainty relation, the violations of classical energy conservation law are possible in quantum system, if the time interval satisfies $\Delta t\sim\hbar/\Delta E$.

The Heisenberg's uncertainty principle is the aftereffects of the interference between the apparatus and the quantum object. However, that is not to say that the motion of particles will not obey the uncertainty principle, without the performance of measurement. Because of the comparable order of Planck constant with the energy of quantum objects, we cannot neglect the uncertainty arising from the effects of Planck constant at all. Therefore, the uncertainty principle does not depend on the degree of accuracy of the apparatus and also has no any relation to whether the observers do the measurements, which just results from the intrinsic uncertainty of the quantum objects and manifests via the measured results when performing a measurement. Considering the uncertainty relation, we can just obtain the statistical properties of a quantum system. So, we should measure the state of a system for many times, and the statistical average of the measured values is meaningful. As a consequence, the determinism cannot be the philosophical foundation for the law of a quantum system.

Bohr's Principle of Complementarity

Because we cannot remove the interference of the apparatus when measuring the state of quantum objects, the states involving in the quantum realm actually are not the real states, but the results interacting with the classical apparatus. Accordingly, the quantum objects and the apparatus are both interdependent and inseparable. In order to describe the quantum phenomena of the micro-world in classical language, Niels Bohr proposed the concept of "complementary principle" in 1927 and explained two kinds of manifestations as both wave and particle for a quantum object. According to Weiner Heisenberg, the "wave" and "particle" are two different manifestations in describing the quantum phenomena, both of which can give a complete description for the quantum objects, and the degree of completeness depends on the uncertainty principle. However, N. Bohr believes that we need to use the complementarity of both "wave" and "particle" and gives the complete description for a quantum object, instead of just one form, and the degree of accuracy is subject to the uncertainty principle.

We can summarize the complementary principle [6] as four aspects. (1) The determination and measurement for the state of particles are exclusive and complementary. During the process of measurement, the particle and apparatus interact with each other. We need to avoid the interaction and the interference with the motion of the particle, in order to determine the state of the particle with more accuracy. Accordingly, the observation and the determination of the state of quantum objects are contradictory existences. If one is satisfied, the other will not be satisfied anyway. (2) The causality description and space-time description are exclusive and complementary. The macro-phenomenon obeys the causality, without any interference. In the experiments of micro-phenomenon, the interference always appears inevitably, which results in that the causality is replaced by the probabilistic statistics. In the classical framework, we usually use the space-time coordinates and describe the causality of macro-objects. While in the quantum theory, there is uncertainty relation for the state of motion described by the space and time. Therefore, we cannot describe the motion of quantum objects in space and time, with the expression of mathematical causality. That is to say, we cannot describe the quantum system with space-time and causality simultaneously, and how we choose the description should follow the statistical probability. (3) The two kinds of classical concepts, i.e. "wave" and "particle", are exclusive and complementary. When describing the quantum objects, we need to use both "wave" and "particle". However, we cannot use them simultaneously, because of the restriction of Heisenberg's uncertainty principle. So, "wave" and "particle" are independent with each other and supplementary to each other, and their combined descriptions give us the complete knowledge of the quantum objects. Taking an example, if we can measure the momentum of an electron with sufficient degree of accuracy, in which we describe the electron as a "particle", the space-time coordinate of the electron then cannot be determined at all. Consequently, the electron just can present as "wave packet", in which we use the "wave" language. Accordingly, the two kinds of contradictory concepts are supplementary to each other when describing a quantum object, and the combined description completely characterizes the characteristics of the quantum objects. (4) The apparatus and arrangement for the experiments are exclusive and complementary. The complementarity of "wave" and "particle" inevitably leads to contradictoriness and complementarity of the apparatus and arrangement when designing an experiment.

Although both the Heisenberg's uncertainty principle and Bohr's idea of complementarity are the interpretations for the wave-particle duality of quantum objects, the foundation of Bohr's idea of complementarity is the Heisenberg's uncertainty principle, while the Heisenberg's uncertainty principle is the specific expression of the Bohr's idea of complementarity. The uncertainty relation is the mathematical expression of the quantum mechanics, while the principle of complementarity gives interpretation to the observable quantities.

Philosophical Analysis for Copenhagen Interpretation:-

According to Mach's philosophy of positivism, the survival and development of scientific theory or concept must be based on the experimental observability. The study for the nature of things cannot do without observations. The starting point of the research lies in the measurements of observable quantities. Mach's philosophy had deep impact on the Copenhagen school of thought, which believes that physics is a kind of observable and testable science and that the theory must be observational and tested. We put forward theory on the basis of experiments and predict the probability of experiments according to the theory. In this regard, quantum mechanics aims to find the relations between physical observables in quantum realm. The behaviors of quantum objects can only be understood via measurements, during which the interactions alter the states of quantum objects. Each quantity describing the quantum theory must be experimental observables. According to Copenhagen school of thought, it doesn't make any sense to talk about any things without experiments, and physics is the science about operation in experiment. For the things that one cannot explain clearly and make us to understand, it is best to keep in silence. In this sense, it is said that quantum physics is the discipline about the subjective cognitive world, instead of the objective real world, which is the reason why Copenhagen school of thought has been considered as positivism, idealism, and observatism. Niels Bohr insisted on both the positivism and traditional philosophy. However, Weiner Heisenberg claimed that the Copenhagen interpretation describes the micro-world by means of classical concepts, which belongs to reality category, instead of the positivism based on the subjective perception [7].

On the point of view of determinism, we can determine the state of a particle at t_2 according to its equation of motion and its state at t_1 in classical framework of physics, which tightly follows the causality determinism. However, in the quantum theory, we just can figure out the probabilistic distribution of the state at t_2 from the state of the particle at t_1. Before the measurement, the evolution of Schrödienger wave equation obeys causality [8, 9], which yet can just gives the probabilistic description for the state. So the statistical interpretation and classical determinism, essentially, conflict with each other. According to Copenhagen school of thought, quantum theory essentially obeys the statistical law, instead of determinism, which requires giving up the deterministic mode of thinking [10]. The uncontrollable interference of classical apparatus with the quantum objects makes us to have no choice but to give up the causality in describing the quantum phenomena. The descriptions of quantum phenomena by both Heisenberg's matrix mechanics and Dirac's quantum number finally lead to the abandon of determinism and turns to the non-deterministic statistical theory, which implies that the non-deterministic statistical law is both the substantive characteristics and the essential differences between quantum theory and classical physics. However, Einstein strongly opposed the statistical concepts. He, following Heisenberg's uncertainty principle, suggested a series of experiments against the complementary principle, such as the "light box". It was proved that Einstein's analysis was illogical. Then he turned to question the complementarity of Copenhagen interpretation of quantum mechanics. During the development of quantum theory, many people challenge Copenhagen interpretation, which still yet dominates our understanding of quantum phenomena. Most of us insist that the statistical probability and wave-particle duality are the nature of micro-objects, which leads to Heisenberg's uncertainty principle and reflects the special characteristics of quantum objects. Hence, the time causality is replaced by the statistical causality. Either statistical causality or statistical determinism indicates that the states of quantum objects at different moments relate to each other according to probabilistic causality.

On the point of view of realism, the matter is the objective and realistic existence, which is independent on the observer's volition, according to the traditional view of realism. That is to say, the states and intrinsic properties of observable objects, which are independent of consciousness, are independent of the experimental operation.

However, the quantum objects and apparatus are inseparable in quantum measurement, according to Copenhagen school of thought. We have to learn the properties and states of quantum objects with the aid of classical apparatus, and there are no any micro-objects that can be independent of observations. Besides, the understanding of uncertainty principle also needs the intervention of observers. Consequently, the Copenhagen interpretation actually introduces the idea of subjectivism into the measurements, i.e. “the perceptive subject influences the perceptive object”, which, to some extent, results in conflict with the traditional concept of realism. As a result, the topics around realism are widely disputed, e.g. “whether the wave function is physical reality or subjective cognition”, “is there any objective reality independent of the subjective cognition”, and so on. Weiner Heisenberg claimed that the mathematical descriptions tell us the cognition of behavior of quantum objects, instead of the behavior of the particles itself, and that the concept of objective reality disappears in the mathematical descriptions. According to Niels Bohr, the particles depend on classical apparatus, and the measurements result in the irreversibility of the states of both particles and apparatus. When the measurements end, the quantum objects manifest themselves as the eigen-states, and the readings of the apparatus show the eigen-values of the particles. Both the readings of apparatus and the states of particles cannot return to the original states before the measurements. In this sense, we cannot talk about the quantum objects without the consideration of observational conditions. However, there is obvious distinction between the quantum objects and the classical apparatus. We always describe the particles as quantum objects and consider the apparatus as classical one, which leads to the unavailability of classical realism in the quantum domain. It can be seen that Bohr’s concepts of quantum measurements reflect the idea of holistic realism. Accordingly, the quantum theory isn’t the description for the quantum reality, but the cognition and concept for the quantum reality, from the analysis of point of view of realism.

On the point of view of epistemology, there are two different forms of wave function before and after the measurements. Before the measurement, although the wave function follows the Schrödienger wave equation, it is actually not the eigen-state of the measured mechanical quantity. When the measurements end, both the quantum objects and the apparatus appear as their eigen-states. Accordingly, the wave function collapses into the eigen-function of the measured mechanical quantity. Niels Bohr tried to explain such process by using the classical concepts and uncontrollable interactions. In analogy with the subjective perception of saltus, Weiner Heisenberg proposed the quantum transition during the measurements. According to von Nenmann’s theory of measurement, in order to avoid the inferences between the apparatus and the quantum objects, we need to introduce the second apparatus, the third apparatus, …, and so on, which forms an infinite loop of instrument chain. The infinite loop just can be truncated factitiously and then leads to the reduction of wave packet, which turns the physical problems to psychological problems but is logical self-consistent in the intuitionistic theory of physics. However, it falls into the dualism of body and mind in the philosophical epistemology. Consequently, the “wave packet” or “reduction of wave function” is not just a physical problem but also an epistemological problem.

Summary and Discussions:-

There are many points about Copenhagen school of thought about the quantum mechanics. Despite of their confusions, there is one common point, i.e. the overemphasis of the significance of consciousness and observers in understanding the physical objects. Taking some examples, Niels Bohr claimed that we cannot understand micro-world without observations, Weiner Heisenberg believed that the interference between particles and apparatus needs the observers, and von Neumann insisted that the collapse of wave function occurs in the consciousness. These points, undoubtedly, cause the subjective idealism and the collisions with materialistic epistemology.

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