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RECENT TRENDS IN THE INTERPRETATION OF QUANTUM MECHANICS

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Max Planck discovered the existence of quanta one century ago and the basic laws of this new kind of physics were found in the years 1925-1926. They have since withstood the test of time remarkably well while giving rise to a multitude of discoveries and extending many times their field of validity. Quantum mechanics was certainly the most important breakthrough in science in the past century with its influence on physics and on chemistry and beyond, including many features of molecular biology.

Almost immediately, however, it was realized that the new laws of physics required that the foundations of the philosophy of knowledge be drastically revised because quantum rules conflicted with various deep traditional assumptions in philosophy such as causality, locality, the realistic representation of events in space and time, and other familiar ideas. For a long time, the so-called Copenhagen interpretation provided a convenient framework for understanding the quantum world of atoms and particles but it involved at least two questionable or badly understood features: a conceptual split between quantum and classical physics, particularly acute in the opposition between quantum probabilism and classical determinism, and a mysterious reduction effect, the "collapse of the wave function", both difficulties suggesting that something important was still to be clarified.

Much work is still presently going on about these foundations, where experiments and theory inspire and confirm each other. Some results have been obtained in the last two decades or so, probably important enough to warrant your attention and I will try to describe a few of them.

VON NEUMANN'S THREE PROBLEMS

I believe the best way to introduce the topic will be to show it in a historical perspective by going back to the work by Johann (later John) von Neumann. In a famous book, *Mathematische Grundlagen der Quantenmechanik,* published in 1932, he identified some basic problems.

It may be interesting to notice that von Neumann was a mathematician, indeed among the greatest of his century. This was an asset in penetrating the essentials in a theory, quantum mechanics, which can be characterized as a typical formal science; that is to say a science in which the basic concepts and the fundamental laws can only be fully and usefully expressed by using a mathematical language. He was in addition a logician and he had worked previously on the theoretical foundations of mathematical sets. That was also a useful background for trying to master the quantum domain where logical problems and possible paradoxes were certainly not easier than those arising from sets.

It is also worth mentioning that von Neumann had been a student of David Hilbert, and Hilbert's conception of theoretical physics was very close to the contemporany trends in research. He thought that a mature physical theory should rest on explicit axioms, including physical principles and logical rules, from which the theory had to be developed deductively to obtain predictions that could be checked by experiments.

Von Neumann contributed decisively (along with Dirac) to the formulation of the basic principles, unifying the linear character of quantum states with the non-commutative properties of physical quantities within the mathematical framework of Hilbert spaces and defining dynamics through the Schrödinger equation. He also made an important step towards "interpretation", but this is a protean word that must be explained. It can mean interpreting the abstract theoretical language of physics into a common-sense language closer to the facts and experiments, just like an interpreter would translate a language into another; but interpretation can also mean "understanding" quantum physics, notwithstanding a drastic epistemic revision if necessary. We shall use the word with both meanings but von Neumann's contribution, which we are about to discuss, was definitely a matter of translation.

He assumed that every significant statement concerning the behavior of a quantum system can be cast into the form of an "elementary predicate", a statement according to which "the value of some observable A lies in a range Δ of real numbers" (By now, this assumption has been checked in all kinds of circumstances). He also found, as a consequence of his investigations on quantum observables, that a predicate of that kind can always be associated with a definite mathematical object, namely a subspace of the Hilbert space or, equally as well, the operator of projection over the subspace. The main point in the second version is that a projection operator can only have two values ("eigenvalues"), which are 0 or 1. We are now accustomed from the logic of computers (to which von Neumann contributed later decisively) to the fact that 1 can mean "true" while 0 means "false", so that projection operators can implement Aristotle's rule for the definite truth of propositions while using a basically probabilistic theory.

The proposal was both deep and potentially useful, since it provided a convenient language for the description of physical events, a language that was, moreover, directly rooted in the principles of the theory. Its existence might have had a great influence on interpretation but, unfortunately, it was immediately disregarded because of three dire difficulties. Von Neumann himself observed them as follows:

1. After devising a model for a measurement where the system to be measured and the measuring apparatus both obey quantum mechanics, he found the apparatus to be generally in a state of superposition, representing one measuring result *and* other ones. Since measuring devices are macroscopic, this meant the existence of macroscopic superpositions if quantum mechanics is universal, whereas such states are never observed. This difficulty became famous a few years later when it was explained by Schrödinger with a cat included in the device.

2. Physics becomes classical at a macroscopic level, but classical properties are not simple predicates. They refer not to the range of values for *one* observable but generally to two non-commuting physical quantities such as position and momentum, whose values are given together within some range of possible error. Von Neumann did not succeed in extending to classical properties the translation of a predicate by a projection operator. It looked, therefore, as if his language was restricted to atoms and particles and was deprived of universality.

3. The last difficulty jeopardized in some sense the whole process: If every elementary predicate is considered as a possible proposition, the language makes no sense because it cannot satisfy the elementary rules of standard logic.

THREE ANSWERS

The progress that has recently been accomplished in interpretation is best expressed by saying that von Neumann's three problems have now been solved. Let us review the answers.

Macroscopic superpositions versus decoherence

The problem of Schrödinger's cat never existed because of a physical effect, which is called decoherence. Its origin is to be found in the fact that the wave function of a macroscopic object does not depend only on the few collective quantities which are effectively measured or controlled, such as the position of a pointer on a voltmeter dial or the electric potential in a computer memory. The wave function depends typically upon some 10^{27} degrees of freedom or so, to take care of the internal atoms, the electrons inside the atoms and outside, the atmosphere molecules around the object and photons in surrounding light. All these uncontrolled degrees of freedom describe what is called the *environment* of the object, although there is as much internal "environment" as external.

Decoherence is easy to understand if one thinks of a pointer on an old-fashioned voltmeter dial. Let us consider a case where the voltmeter registers the result of a quantum measurement and does it by having the pointer pointing vertically up or down according to the measurement result. The crux of the Schrödinger cat paradox is to deal with a quantum state where the two positions "up" and "down" are superposed and the possibility of observing interferences between the two positions.

But think of what really happens. When the pointer begins to move towards the "up" position, the atoms near the pointer axis suffer some sort of a cataclysm or, at least, their partial wave functions are strongly affected, with wild changes in their local phase. The same thing happens when the pointer moves towards the "down" position, except that the environment wave function has no reason to keep any sort of phase coherence with its value in the "up" motion. This is the decoherence effect, which suppresses every possibility of quantum coherence between "up" and "down", every kind of interferences between them: the state of the pointer is only *either* "up" *or* "down" as it would be in a standard probabilistic description.

After being recognized [1], the decoherence effect began to be investigated on models, from which quantitative results were first obtained: it is by far the most efficient quantum effect acting at a macroscopic level. Later, it was recognized as a more or less standard kind of irreversible process. For a long time, it could not be observed experimentally for a rather peculiar reason, because it is so quick that it has already acted before one can see it in action. Finally, it was observed not long ago, with excellent agreement between the predictions and the observations [2]. Clearly, older considerations about reduction (wave function collapse) must take this important result into account.

Classical properties versus mathematics

A powerful technique was developed by mathematicians in the seventies for studying linear partial differential equations and related topics. It is called “microlocal analysis” or “pseudo-differential calculus”. Two basic results from this theory have yielded an answer for the second von Neumann problem. The first is concerned with a classical property allowing large errors in position and momentum as compared with Heisenberg’s uncertainty limit. A theorem says that such a property of that kind cannot be associated with a unique projection operator in Hilbert space but anyway, it is very well represented, qualitatively and quantitatively, by a set of “equivalent” projection operators.

Another theorem says how quantum evolution acts on these representative operators, in a way reflecting almost exactly the evolution of the classical property under classical dynamics. It means in a nutshell that the old and rather fuzzy “correspondence principle” has been replaced by explicit and precise statements, which directly derive from the true principles (Hilbert space formalism and Schrödinger dynamics). Another way to express these results would be to say that the von Neumann language using projection operators is universal: it can describe classical physics, classical situations, just as well as it suits quantum properties. One must therefore certainly revise the Copenhagen standpoint according to which physics had to be split into a classical domain and a quantum one, both having independent laws except for the loose connection of “correspondence”.

Standard logic and consistent histories

The last problem, namely the apparent conflict between the language of projection operators and standard logic, has also been solved by finding the right “grammar” for the language, in terms of so-called “consistent histories” [3]. The idea is to restrict explicitly a description of physical events by expressing it through a time-ordered sequence of relevant statements, which are either predicates (about atoms and particles) or classical properties (about macroscopic devices: preparation and detection for instance). Each statement of either kind is associated with a projection operator. Explicit “consistency conditions”, which are equations involving these operators and the initial state, make sure that there exists a probability distribution (on a “family” of histories reviewing the various possible occurrences). Quite remarkably, it was also found that standard logic holds inside such a family of consistent histories and no “exotic” logic is necessary for interpretation.

A simple example of how the theory works is provided by a famous example from an interference experiment: it is indeed logically impossible to assert that a photon (or an atom) went through a single arm of an interferometer, because the corresponding histories do not satisfy the necessary consistency conditions. Conversely, the language most frequently used in books and papers on physics, in which cautious rules cleverly avoid paradoxes, can be fully justified from the consistency of the underlying histories.

Finally, a strong connection between the three kinds of new results should be mentioned: decoherence ends up most often with a classical situation, and logical consistency is also most often a consequence of decoherence or of the recognized validity of classical physics.

A NEW INTERPRETATION

Using the answers to the three problems, interpretation can be cast into a completely deductive sub-theory inside the theory of quantum mechanics [4]. Its physical axioms have been already mentioned (i.e., the Hilbert space framework and Schrödinger dynamics) whereas the logical axioms amount to the use of von Neumann’s language under the constraints of consistent histories. The well-known rules of measurement theory are among the main results and they have become so many theorems in this approach. A few other aspects are worth mentioning:

– Probabilities become still more intimately linked with quanta. In this approach, they appear first in the logical axioms (where they define logical implication) and from there on one can prove (in the resulting logic) the necessity of randomness among physical events. This new vision of probabilities may be rather deep but its implications are not yet fully appreciated.

– Three “privileged” directions of time must enter the theory: one in logic (for the time ordering of predicates in histories), one for decoherence (as an irreversible process), and the familiar one from thermodynamics. The three of them must necessarily coincide. The most interesting aspect of these results is certainly that the breaking of time reversal symmetry is not primarily dynamical but logical and a matter of interpretation, at least from the present standpoint.

– There is only one kind of basic laws in physics in this construction, and they are quantum laws. The validity of classical physics for macroscopic bodies (at least in most circumstances) emerges from the quantum principles. In particular, classical determinism can be proved to hold in a wide domain of application. Its conciliation with quantum probabilism is finally very simple if one notices that determinism claims essentially the logical equivalence of two classically meaningful properties occurring at two different times (one property specifying for instance position and velocity for a tennis ball at an initial time and the other property being similar for reception at a later time). Their logical equivalence holds *with a very small probability of error*. This very small (and known) probability of error allows determinism to assume a probabilistic character, although a very safe one.

PHILOSOPHICAL CONSEQUENCES

It should be stressed first of all that this approach brings nothing new concerning the reality of quantum properties. Complementarity is still there and even more so, because it is now a trivial consequence of the history construction. The most interesting philosophical consequences are therefore concerned with the understanding of classicality in the ordinary world of macroscopic objects or, in a nutshell: why is common sense valid?

The technical answer to this question lies in considering histories where only classically meaningful properties of every kind of macroscopic objects enter. There is no problem of complementarity with such histories and therefore no problem with reality: the set of consistent histories describing our common experience turns out to be unique, sensible (i.e. satisfying the relevant consistency conditions), and the logical framework resulting from the quantum axioms in these conditions is what we might call “common sense”. *There is therefore no conflict between quantum theo-*

ry and common sense and the first implies the second, except that one should be careful not to extend excessively the domain where common sense is supposed to be valid.

More precisely, one may refine common sense by making explicit in it familiar and traditional philosophical assumptions: causality (or determinism), locality in ordinary space, separability (except for measurements of an Einstein-Podolsky-Rosen pair of particles), reality (as used in a philosophical discourse, i.e. the consistency of all the – classical – propositions one may assert about the – macroscopic – world). The fourth has just been mentioned and the three first share a common character: they are valid at a macroscopic scale, except for a very small probability of error (or invalidity). When one tries, however, to extend them towards smaller and smaller objects, the probabilities of errors keep growing and finally, when one arrives at the level of atoms and particles, these traditional principles of the philosophy of knowledge have such a large probability of error that they are plainly wrong.

There is a lesson in this: When dealing with *physis*, the principles that have been reached by science after much work stand on a much firmer basis that many traditional principles in the philosophy of knowledge. The concepts and laws of physics have been checked repeatedly and very carefully in a wide domain and, as indicated in this talk, they imply the validity of older more philosophical principles in ordinary circumstances. Conversely, the old principles are limited in scope and the purpose of understanding in their light the essentials of quantum mechanics is illusory. Some sort of a "premiss reversal" in the philosophy of knowledge is therefore suggested [5].

Open questions

Some important questions are still a subject of controversy. All of them revolve around a central one: why or how is there a unique datum at the end of a measurement? Some questions concerning the ultimate meaning of decoherence are very close to this problem of actuality, or objectification, and the diversity of the proposed answers is too wide for them to be mentioned here. My own inclination goes towards an apparently new direction, which is why I mention it, addressing myself particularly to the philosophers and theologians in this Academy. I wonder whether the question of actuality is a problem *in* physics or *about* physics. In the second case, it would open wide philosophical perspectives, the most obvious one being a renewal of the old question: up to what point does physics reach reality and, outside this reach, should it be said to preserve appearances? After all, everything we observe can be derived directly from the quantum principles except for the uniqueness of empirical reality, but this uniqueness can be shown to be logically consistent with the basic principles, or preserved by them. More generally, I think we should be more inquisitive about the essential role of mathematics in basic science, considering that we do not know conclusively what is the status or the nature of mathematics. One may question particularly the possible limits of the “Cartesian program”, according to which one assumes – perhaps too easily – the possibility of a mathematical description for every aspect of reality.

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