International Journal of Theoretical Physics, Vol. 31, No. 9, 1992

The Subject Matter of Quantum Mechanics

Michael Drieschner[1]

Received February 10, 1992

This is a philosophical paper. It deals with the interpretation of quantum mechanics, i.e., with reality, the objects of quantum mechanics, probabilities, etc. It is important to distinguish between real things and physical systems. A physical theory is a collection of rules for predictions on the outcome of measurements. Contrary to general belief "prediction" and "possible and actual" are key concepts in physics, as well as the concept of probability, being the most general empirically testable prediction. The Copenhagen interpretation is nothing but a "minimal semantics" of quantum mechanics, dealing with possibilities rather than with facts. Quantum mechanical realism is the futile attempt to confine physics to the description of facts. We answer the old question whether probability is about single events or about series of events: it can be about either, if it is correctly interpreted as a representative of the abstract ensemble. Quantum mechanics is only interesting if it is the most general theory of all possible systems. But this is where the hard problems arise: measurement, reality, indeterminism, etc. These problems can be solved if we accept seriously the key role of prediction and possibility, and abandon the ontology of classical physics.

This paper concerns a rather general question, not directly related to mathematical formalisms of quantum logic. But I think that general considerations of this kind are indispensable if one tries to clarify the fundamental questions of science. We shall come in touch with more technical questions in the course of the paper.

At first sight it seems rather silly to discuss the subject matter of quantum mechanics: everybody knows that quantum mechanics is about atoms, nuclei, elementary particles, and their fields; in short: quantum mechanics is about micro-objects.

If this were all there is to it, it would not be worthwhile to treat the question in a paper. We are all interested in quantum mechanics not because it is the theory of some exotic specialty called "micro-objects," but because it is supposed to be the most general physical theory we know to date about

---

[1] Ruhr-Universität, Bochum, Germany.

our world. This is so because we are convinced that all objects consist actually of molecules, which in turn are composed of atoms, which, again, are composed of elementary particles. So the theory of micro-objects is, in fact, the theory of all objects, it is the theory of reality in general.

Here the difficulties begin. Since the days of Bohr and Einstein the battle between "realists" and "Copenhagenians" about how quantum mechanics describes reality seems to have raged undecided. I would like to shed some light on this battle, beginning with a fundamental distinction.

1. THINGS AND PHYSICAL SYSTEMS

In order to apply physics to reality, you have to idealize reality. This means, first, that you split reality into separate entities, and second, that you consider only certain qualities of those entities, namely those that occur in the theory you want to apply. E.g., if you deal with astronomy, you consider planets and the sun as separate entities, and you take every one of them as a point mass, i.e., something whose state is fully described by position and momentum. The situation can be analyzed, for all physical theories that exist today, in the following way: A planet or an apple falling from Newton's apple tree is what I call a thing. A point mass, on the other hand, is a physical system. It belongs, in this case, to the theory "point mechanics." A physical system is only defined with respect to a certain theory; it is the entity whose state is given by the observables of that theory, in the case of point masses by position and momentum. Thus, the physical system of point mechanics is the point mass, the simplest physical system there is. But you can describe the same thing—for example, Newton's apple—as a rigid body, another (idealized) physical system, whose state is described, to begin with, again by position and momentum (of the center of gravity, as one says in that theory), and in addition by its orientation in space and its angular momentum. The physical system of thermodynamics, to take a different example, is the "thermodynamic system," described, e.g., by its temperature, volume, and pressure. Thus, in a certain sense, a physical system is made out of its observables.

2. PREDICTIONS

The amazing success of physics rests upon the fact that you can predict the future behavior of real things in a very good approximation with the theory of the corresponding physical systems. Or, to put it the other way round: You can choose physical systems and theories in such a way that, knowing the present values of all observables that constitute the physical system (its present state) enables you to predict the values of those same observables in the future. You can take this as a definition: a physical system (of a physical theory) is the abstract combination of a certain set of observables in such a way that a prediction of all these observables is possible using only the past values of those same observables.

If you analyze physics in this abstract way, you find that it is basically a bunch of rules for predicting future results of measurements on the basis of past measurements—by the mediation of physical systems.

Such a rule is called a law of nature. Everybody knows that a law of nature has the form: "If you do this and that, then you will find such and such results": A law of nature is a general prediction. This may not be the usual form of describing what physics is about. You may in general rather find it put in this way: "Physics describes the fundamental, never changing structure of nature, in an objective way." But what does that mean? An objective description of the structure of nature is one that, in principle, can be put to an empirical test by anyone. Thus, if you claim to have given such a description, you must maintain that everybody will be able, in principle, to go and make the same measurements you made, and you predict that she or he will find the same results: Objectivity in the sense of science has the form of rules for predictions; the generality of scientific propositions implies their predictive or "futuric" character.

3. POSSIBLE AND ACTUAL

At this point it is important to pay attention to one of the oldest distinctions in the philosophical tradition: Possibility and actuality, *dýnamis* and *enérgeia*, according to Aristotle, or, in Latin, *potentia* and *actus*, from which the English words potential and actual are derived. The relation with temporal propositions is quite clear: the past is actual (it consists of "facts"), the future is potential. And since physics deals, by its very nature, with predictions, it deals with potential events, or with possibilities.

In classical physics this structure is obscured by the fact that all predictions are made with certainty. Classical physics predicts for any future result of a measurement either that it will come out or that it will not come out, probabilities are really always one or zero; probabilities unequal to one or zero can only reflect our lack of knowledge. Thus, every prediction in classical physics is of the form, e.g., "When I shall measure the momentum of this car, I shall (with certainty) find 20,000 kgm/sec." We can put it even in its counterfactual form: "If I had measured the momentum, I would have found 20,000 kgm/sec." This can be abbreviated as: "The car has this momentum, in itself." Surely I have to admit that putting the propositions of classical mechanics in this way means viewing it from the viewpoint of quantum mechanics, after all our reflection about probabilities and all that.

But this is the normal way of philosophy: We are philosophizing today, we have learnt from those reflections, we no longer live within the "ontology of classical physics" which supposed naively that the world *is* what classical physics describes.

In quantum mechanics, to the contrary, the result of a measurement is predicted with some probability in the whole range from zero to one, e.g., "The probability that the next particle will hit this part of the screen is 20%." This is a fundamental feature of quantum mechanics as it is today. There have been attempts to present a ("realistic") underlying theory in the light of which quantum mechanics would appear as a theory of lack of knowledge, as thermodynamics does in the light of particle mechanics. But these attempts have so far—to say the least—not given a convincing result. Therefore it is not possible to translate all predictions into propositions about "facts in themselves"; in quantum mechanics we have to take predictions into account quite seriously.

4. QUANTUM LOGIC

This leads us right into the heart of quantum logic: quantum logic is a logic of temporal propositions, namely a logic of predictions. This implies a lot about the structure of quantum logic, two things among others:

1. The conjunction of two noncompatible propositions is again a proposition.
2. Quantum logic is a logic of probabilities.

As to the first point: It is impossible to measure a proposition "$A \wedge B$" if A and B are not compatible. But when interpreted as a prediction, "$A \wedge B$" makes sense if you take into account its conditional character: "If one measures A one will find A, and if one measures B one will find B."

In fact, every proposition "A" has a predictive character. One would state such a proposition in a more explicit form as: "If I (shall) measure A, I shall find A," where A describes a measurement that corresponds to the proposition A. The conjunction of two such propositions makes sense because it combines two possibilities for the future; one still has the choice of which one of the two is to be realized. As long as they are still in the future they are compatible, namely as possibilities. This structure of the conjunction is well illustrated in the "dialogic" foundations of logic (e.g., Lorenz and Lorenzen, 1978). There the conjunction is transformed into the rule: "If the proponent proposes "$A \wedge B$," then the opponent may choose either to challenge A, or to challenge B." The same interpretation is applicable to physical predictions; predicting "$A \wedge B$" means: Whichever of the two you choose to measure, A or B, you will find the prediction true.

The second point deals with the role of probability in nature. It deserves a section of its own.

5. PROBABILITY

Probability is the most general prediction for any empirically testable proposition.

I have to explain this statement: Suppose we are looking for a general rule for predictions on certain outcomes of experiments, a rule of the type we call a "law of nature"; or, to put it in one phrase: we are looking for a general rule for predictions about an empirically testable proposition. Let us call that proposition A. In a direct approach, in 0th approximation, so to speak, you may predict either that A will come out or that $\neg A$ will come out. This corresponds to the ontology of classical physics, which assumes that A (or $\neg A$, respectively) is *true in itself*. But the most general prediction in that situation would be: "Sometimes A and sometimes $\neg A$ will come out." This is a prediction that does not predict much; you might reformulate it as saying that the probability of A is neither 0 nor 1. In a similar way we can subsume predictions of the "classical" type as always stating probability 1 or 0. Thus, all predictions we know to date are probability propositions. Let us show that this is structurally so, i.e., that every empirically testable proposition must be a probability proposition (Drieschner, 1979). We could argue in the following way:

Consider a series of N measurements of A. The proposition "Sometimes A and sometimes $\neg A$" refers to identical measurements, identical in every respect that is relevant for the measurement.[2] Thus, the order of A's and $\neg A$'s cannot be predicted, only the number of A's (and, consequently, $\neg A$'s) among N measurements is predictable. There must be, according to our supposition of the structure of laws of nature, a general rule for predicting those numbers. Thus, the number n of A's must be a function that depends only on the number N of experiments in a series. Call this function $n(N)$. Because of the "identity" of events it cannot depend on any other feature of a series of measurements but on its number; permutations of "identical" measurements, e.g., would not change anything.

It is evident that this function can only be the relative frequency of positive results A, i.e., n/N. To be sure, let me make the reasoning a bit more explicit:

---

[2] It is impossible to have two events that are identical in every respect: The world will have gone on in the meantime. It is a challenge for ingenious experimenters to find out which conditions are relevant for the experiment and which are not.

Consider two series of N_r and N_s measurements, respectively, as one new series of $N_t = N_r + N_s$ measurements. The number of events A in the new series is described by a new value of the function $n(N)$:

$$n(N_t) = n(N_r + N_s)$$

This new number is the sum of the numbers of A's in the two series:

$$n(N_t) = n(N_r) + n(N_s)$$

Thus,

$$n(N_r + N_s) = n(N_r) + n(N_s)$$

for all N_r and N_s, i.e., the function $n(N)$ is linear:

$$n(N) = \alpha \cdot N + n(0)$$

When there is no measurement, no event A can come out, $n(0) = 0$. Thus, the factor $\alpha = n(N)/N$ fully determines the function, this factor is what can be predicted. The result is:

> Prediction of the relative frequency of A is the most general empirically testable prediction we can make at all about A.

This leads us to define:

> Probability is the prediction of a relative frequency.

Of course, anybody can call probability what he likes, a definition cannot be true or false. But there are useful and useless definitions, and I claim that my definition is useful in that it represents what regularly in physics is meant by the term "probability." Physicists normally do not put it in those terms ("prediction" is such an awfully subjective word!); they would rather say that probability is relative frequency. But it is quite clear that this cannot be so in a strict sense. Think, e.g., of throwing dice. The probability of a six is (normally) 1/6; but the relative frequency can only be 1/6 if the number of throws is divisible by six. As a general rule a probability proposition can only be meant as a *prediction* of relative frequency and it can only turn out true with a certain approximation. We can even predict the quality of such approximation according to the rules of the calculus of probability.

If we take the identification of probability with predicted relative frequency for granted, then what we have shown is that probability propositions are the most general empirically testable propositions, or, to put it in a different way: The most general physical law is a probability law (including the case of classical physics, where all probabilities are, in themselves, 1 or 0).

In this way we have arrived at an insight that is extremely important for the discussion of the foundations of quantum mechanics: The probability character of quantum mechanics is what makes it such an extremely general theory, maybe the most general theory there is at all.

6. THE COPENHAGEN INTERPRETATION OF QUANTUM MECHANICS

Quantum mechanics deals essentially with possibility, not with facts. This is the core of the Copenhagen interpretation of quantum mechanics. The Copenhagen interpretation is the "minimal" interpretation (C. F. v. Weizsäcker) in the sense that it tries not to say anything beyond what is contained in the physical theory itself. Copenhagenians emphasize that quantum mechanics is incomplete in a very important sense: There is no way within quantum mechanics of stating facts. This is especially unpleasant when you deal with measurements, because within quantum mechanics you cannot state the fact that such and such a result has been measured. Classical physics was able to do this because it talked about facts all the time. This is what Niels Bohr meant when he spoke of the necessity of classical concepts. He wrote

> . . . it would be a misconception to believe that the difficulties of the atomic theory may be evaded by eventually replacing the concepts of classical physics by new conceptual forms. Indeed, as already emphasized, the recognition of the limitation of our forms of perception by no means implies that we can dispense with our customary ideas or their direct verbal expression when reducing our sense impressions to order. No more is it likely that the fundamental concepts of the classical theories will ever become superfluous for the description of physical experience. The recognition of the indivisibility of the quantum of action and the determination of its magnitude, not only depend on an analysis of measurements based on classical concepts, but it continues to be the application of these [classical] concepts alone that makes it possible to relate the symbolism of the quantum theory to the data of experience. . . . As mentioned above, only with the help of classical ideas is it possible to ascribe an unambiguous meaning to the results of observation. We shall, therefore, always be concerned with applying probability consideration to the outcome of experiments which may be interpreted in terms of such conceptions. (Bohr, 1934)

7. REALISM

Now what about the title of this paper; what is quantum mechanics "really" about? Einstein called quantum mechanics "incomplete," as I did before, but for a different reason: He said that in a complete theory every "element of reality" must have a counterpart in the theory, and according to Einstein, quantum theory is incomplete in this sense—the well-known

EPR paradox. This conception of a theory being some sort of idealized image of reality presupposes that there is something like a reality—"out there"—that can be imaged in some way. This is the fundamental belief of all realists, as far as I understand them.

Realists have good reasons for their belief, because everyone does believe in the existence of the real world, at least in their actions, even if they pretend not to believe in it; a bona fide soloipsist could not even survive. Reality is a very important achievement of evolution: Higher animals, like humans, have the competence of not only reacting immediately on stimuli, but of separating those stimuli from their ego and integrating them into an "objective world" opposed to themselves. When we describe this we are in an awkward situation: on the one hand we describe reality as something that is derived from evolution and not at all self-evident; on the other hand, we describe this as a *real* situation, as part of reality, and we presuppose this reality quite naturally. There is no way out of that circle. Von Weizsäcker (1948) says: "Nature was before mankind, but mankind was before natural science." If we want to make objective science we have to use our inherited "competence of reality." Thus, people who are realists, in a general sense, set off to defend positions that nobody would dare to challenge seriously.

In quantum mechanics, on the other hand, the situation is different. Quantum mechanical realists try to extend the concept of a really existing world "out there" into the realm of the physical systems of quantum mechanics. All I said until now may serve to make it clear that such an assumption is groundless. Reality, in the context of quantum mechanics, consists of the laboratory equipment: bubble chambers, magnets, computers, etc. The physical systems within the fundamental theories—electrons, pions, etc.—have no direct "thing" counterparts; they serve to connect our real equipment in order to make systematic predictions possible.

As consequent Copenhagenians we could state about "reality" something like this: "What we consider real, the world of our everyday life, can be described as it is only in terms of classical physics. What quantum mechanics describes are certain relations between real things, and for this description it uses the concept of a physical system, which comprises more than idealization of real things. In this sense the physical systems of quantum mechanics are the less real the more typically they are quantum mechanical."

8. THE SUBJECT OF PROBABILITY PROPOSITIONS

There is still another objection concerning the objects of quantum mechanics, raised mainly by realists:

"Quantum mechanics gives, as its result, a probability; and a probability can only be measured as a relative frequency in a series of measurements. Thus, quantum mechanics does not deal with individual objects but rather with some strange kind of mental combinations of objects that are not real at all."

Not considering the question of what is "real" and what is not, this is an old problem in the foundations of probability theory: Does a probability statement refer to a single event, or does it only mean anything if referred to a series of events?

This is a very difficult question with a long history; it does not especially concern quantum mechanics, but it is a problem of every probability theory. I can only give a short hint at what I think is the solution: On the one hand, a single event always happens or it does not happen; there is nothing in between. So it is hard to see what a probability statement would mean if applied to a really singular event. On the other hand, applying probability to a series of events instead of a single event would not solve our problem. For a definite series of, say, 10,000 events is a new event, again one event, just as singular as the original singular event was. A probability proposition is actually a general proposition about *any series* of events that consists of identical copies of the original event.

Those "identical copies" are never really identical, but they must be identical as far as it is necessary for the probability to be applicable, and thus the original event cannot be truly singular, but it must be defined conceptually in such a way that repetition, a series of like events, is possible.

This is—probably—what Gibbs (1902) had in mind when he wrote about the "ensemble." An ensemble is some assembly of events, but not a definite series, rather a very abstract collection of all possible series.

Considering the shortcomings of both formulations—namely (i) that probability is about a single event, and (ii) that probability is about a series of events—one could accept both, provided we add the necessary caveats: it is about a single event as far as this event is taken as a representative of all possible series of "identical" events (containing from one to as-many-as-you-like single events); it is about a series of events, as long as this series is not considered this singular series, but as a representative, again, of all possible series, or of the "ensemble."

9. UNIVERSALITY

The Copenhagen view of reality solves the problems of the interpretation of quantum mechanics perfectly as long as quantum mechanics is considered a special theory of micro-objects. But now consider what I call its universality: reality itself is, according to the general view of physicists, made up of micro-objects; therefore all theories of reality should, in principle, be derivable from the theory of micro-objects. It is also the Copenhagen view that quantum mechanics is the general and universal theory of all possible objects. Thus, the question remains: Can reality be made of something that is less real, or not real at all?

I think it can! If we do not adopt the realist presupposition that there is reality somehow "out there," the interpretation is acceptable that real things are only *potentially* composed of elementary particles; that we can find such and such components if we make an experiment that is able to show that type of component. We know from the formalism of quantum mechanics that a compound object may be considered as composed of certain components in some states, but in others, in fact in almost all states it cannot be considered as consisting of those components.

The prejudice is widespread, but nevertheless it is a prejudice that the realist view of the world is obligatory; I do not even believe that it is possible. The science of our century—quantum mechanics, and, in our days, cognitive science—has drawn our attention to a truth that good philosophers have always known: Reality, objectively described, is one way humans deal with the world, but there are many other ways besides this one. It is the special interest in truths that everyone can check for themselves that leads us to objective descriptions. It is a special caution or distrust that compels us to seek such truth.

We should, therefore, be glad that our everyday world, the "mesocosmos," as Vollmer (1975) calls it, can be treated as a real world that is there; otherwise we could not exist. But we should not expect to find a similarly "real" world still behind. It is amazing that physics works that well even in dimensions that are so remote from our everyday life; I am more and more stupified about that wonder of human thinking. But we should keep aware of the fact that all this is human construction in order to get systematic rules for empirically verifiable predictions. We are even able to deduce the rules of quantum mechanics to a large extent from the idea that quantum mechanics should be the most general theory of such predictions. But this would be the subject for another, more technical paper (Drieschner, 1979, 1981).

To conclude I shall try to answer my initial question, what quantum mechanics is about:

Quantum mechanics is about reality, it is even the most general theory of reality there is. But reality is not a concept that is as general as 19th century physicists believed. It has a very intricate "circular" conceptual structure. Only one, although indispensable face of this structure presents itself conforming to the ontology of classical physics.

REFERENCES

Bohr, N. (1934). *Atomic Theory and the Description of Nature*, Cambridge University Press, Cambridge, pp. 16, 17.

Drieschner, M. (1979). *Voraussage-Wahrscheinlichkeit-Objekt. Über die Grundlagen der Quantenmechanik*, Springer, Berlin, pp. 86ff.

Drieschner, M. (1981). *Einführung in die Naturphilosophie*, Wissenschaftliche Buchgesellschaft, Darmstadt.

Everett. H. (1957). Relative state formulation of quantum mechanics, *Review of Modern Physics*, **29**, 454.

Gibbs, J. W. (1902). *Elementary Principles of Statistical Mechanics*, New York.

Lorenz, K., and Lorenzen P. (1978). *Dialogische Logik*, Wissenschaftliche Buchgesellschaft, Darmstadt.

Vollmer, G. (1975). *Evolutionäre Erkenntnistheorie*, Hirzel, Stuttgart.

von Weizsäcker, C. F. (1948). *Die Geschichte der Natur*, Vandenhoeck & Ruprecht, Göttingen.