Albert Einstein, "Quantum Mechanics and Reality" (1948)

[*Dialectica*, 2 (1948): 320-324]

In what follows I shall explain briefly and in an elementary way why I consider the methods of quantum mechanics fundamentally unsatisfactory. I want to say straight away, however, that I will not deny that this theory represents an important, in a certain sense even final, advance in physical knowledge. I imagine that this theory may well become a part of a subsequent one, in the same way as geometrical optics is now incorporated in wave optics: the inter-relationships will remain, but the foundation will be deepened or replaced by a more comprehensive one.

Consider a free particle described at a certain time by a spatially restricted ψ-function (completely described - in the sense of quantum mechanics). According to this, the particle possesses neither a sharply defined momentum nor a sharply defined position. In which sense shall I imagine that this representation describes a real, individual state of affairs? Two possible points of view seem to me possible and obvious and we will weigh one against the other:

> (a) The (free) particle really has a definite position and a definite momentum, even if they cannot both be ascertained by measurement in the same individual case. According to this point of view, the ψ-function represents an incomplete description of the real state of affairs. This point of view is not the one physicists accept. Its acceptance would lead to an attempt to obtain a complete description of the real state of affairs as well as the incomplete one, and to discover physical laws for such a description. The theoretical framework of quantum mechanics would then be exploded.
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> (b) In reality the particle has neither a definite momentum nor a definite position; the description by ψ-function is in principle a complete description. The sharply-defined position of the particle, obtained by measuring the position, cannot be interpreted as the position of the particle prior to the measurement. The sharp localisation which appears as a result of the measurement is brought about only as a result of the unavoidable (but not unimportant) operation of measurement. The result of the measurement depends not only on the real particle situation but also on the nature of the measuring mechanism, which in principle is incompletely known. An analogous situation arises when the momentum or any other observable relating to the particle is being measured. This is presumably the interpretation preferred by physicists at present; and one has to admit that it alone does justice in a natural way to the empirical state of affairs expressed in Heisenberg's principle within the framework of quantum mechanics.
> According to this point of view, two ψ-functions which differ in more than trivialities always describe two different real situations (for example, the particle with well-defined position and one with well-defined momentum).

The above is also valid, mutatis mutandis, to describe systems which consist of several particles. Here, too, we assume (in the sense of interpretation Ib) that the ψ-function completely describes a real state of affairs, and that two (essentially) different ψ-functions describe two different real states of affairs, even if they could lead to identical results when a complete measurement is made. If the results of the measurement tally, it is put down to the influence, partly unknown, of the measurement arrangements.

II

If one asks what, irrespective of quantum mechanics, is characteristic of the world of ideas of physics, one is first of all struck by the following: the concepts of physics relate to a real outside world, that is, ideas are established relating to things such as bodies, fields, etc., which claim a 'real existence' that is independent of the perceiving subject - ideas which, on the other hand, have been brought into as secure a relationship as possible with the sense-data. It is further characteristic of these physical objects that they are thought of as arranged in a space-time continuum. An essential aspect of this arrangement of things in physics is that they lay claim, at a certain time, to an existence independent of one another, provided these objects 'are situated in different parts of space'. Unless one makes this kind of assumption about the independence of the existence (the 'being-thus') of objects which are far apart from one another in space which stems in the first place from everyday thinking - physical thinking in the familiar sense would not be possible. It is also hard to see any way of formulating and testing the laws of physics unless one makes a clear distinction of this kind.

This principle has been carried to extremes in the field theory by localizing the elementary objects on which it is based and which exist independently of each other, as well as the elementary laws which have been postulated for it, in the infinitely small (four-dimensional) elements of space.

The following idea characterizes the relative independence of objects far apart in space (A and B): external influence on A has no direct influence on B; this is known as the 'principle of contiguity', which is used consistently only in the field theory. If this axiom were to be completely abolished, the idea of the existence of (quasi-) enclosed systems, and thereby the postulation of laws which can be checked empirically in the accepted sense, would become impossible.

III

I now make the assertion that the interpretation of quantum mechanics (according to Ib) is not consistent with principle II. Let us consider a physical system S12 which consists of two part-systems S1 and S2. These two part-systems may have been in a state of mutual physical interaction at an earlier time. We are, however, considering them at a time when this interaction is an at end.

Let the entire system be completely described in the quantum mechanical sense by a ψ-function ψ12 of the coordinates q1,... and q2,... of the two part-systems (ψ12 cannot be represented as a product of the form ψ1 ψ2 but only as a sum of such products). At time t let the two part-systems be separated from each other in space, in such a way that ψ12 only differs from 0 when q1,... belong to a limited part R1 of space and q2, ...belong to a part R2 separated from R1.

The ψ-functions of the single part-systems S1 and S2 are then unknown to begin with, that is, they do not exist at all. The methods of quantum mechanics, however, allow us to determine ψ2 of S2 from ψ12 if a complete measurement of the part-system S1 in the sense of quantum mechanics is also available. Instead of the original ψ12 of S12, one thus obtains the ψ-function ψ2 of the part-system S2.

But the kind of complete measurement, in the quantum theoretical sense, that is undertaken on the part system S1, that is, which observable we are measuring, is crucial for this determination. For example, if S1 consists of a single particle, then we have the choice of measuring either its position or its momentum components.
Any "measurement" instantaneously collapses the two-particle wave function ψ12. There is no "later" collapse when measuring the "other" system S2.

The resulting ψ2 depends on this choice, so that different kinds of (statistical) predictions regarding measurements to be carried out later on S2 are obtained, according to the choice of measurement carried out on S1. This means, from the point of view of the interpretations of Ib, that according to the choice of complete measurement of S1 a different real situation is being created in regard to S2, which can be described variously by ψ2, ψ2', ψ2'', etc.

Seen from the point of view of quantum mechanics alone, this does not present any difficulty. For, according to the choice of measurement to be carried out on S1, a different real situation is created, and the necessity of having to attach two or more different ψ-functions ψ2, ψ2', ... to one and the same system S1 cannot arise.

It is a different matter, however, when one tries to adhere to the principles of quantum mechanics and to principle II, i.e. the independent existence of the real state of affairs existing in two separate parts of space R1 and R2. For in our example the complete measurement on S1 represents a physical operation which only affects part R1 of space.
Einstein cannot accept the fundamental fact of "entangled" systems explained to him by Schrödinger, that they cannot be separated.

Such an operation, however, can have no direct influence on the physical reality in a remote part R2 of space. It follows that every statement about S2 which we arrive at as a result of a complete measurement of S1 has to be valid for the system S2, even if no measurement whatsoever is carried out on S1. This would mean that all statements which can be deduced from the settlement of ψ2 or ψ2' must simultaneously be valid for S2. This is, of course, impossible, if ψ2, ψ2', etc. should represent different real states of affairs for S2, that is, one comes into conflict with the Ib interpretation of the ψ-function.

There seems to me no doubt that those physicists who regard the descriptive methods of quantum mechanics as definitive in principle would react to this line of thought in the following way: they would drop the requirement II for the independent existence of the physical reality present in different parts of space; they would be justified in pointing out that the quantum theory nowhere makes explicit use of this requirement.

I admit this, but would point out: when I consider the physical phenomena known to me, and especially those which are being so successfully encompassed by quantum mechanics, I still cannot find any fact anywhere which would make it appear likely that requirement II will have to be abandoned.

I am therefore inclined to believe that the description of quantum mechanics in the sense of Ia has to be regarded as an incomplete and indirect description of reality, to be replaced at some later date by a more complete and direct one.

At all events, one should beware, in my opinion, of committing oneself too dogmatically to the present theory in searching for a unified basis [i.e., a continuous field theory] for the whole of physics.