DEUTSCHES ELEKTRONEN-SYNCHROTRON DESY

DESY 72/64
November 1972

Subject, Object and Measurement

by

R. Haag
II. Institut für Theoretische Physik, Universität Hamburg

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R. Haag

II. Institut für Theoretische Physik, Universität Hamburg

To be published in the Proceedings of the International Symposium "The Physicist's Conception of Nature", held at Trieste, September 1972.

The laws in Quantum Physics are formulated in terms of predictions for the outcome of experiments. Traditionally in physics the motivation for the performance of experiments was the desire to learn about the "outside world", i.e. the world abstracted from the presence of conscious, thinking and planning beings. One may ask first whether Quantum Physics teaches us that such an abstraction is grossly illegitimate. If the answer is no [1),2)] then we may ask further: what can we learn from the laws of Quantum Physics about the properties of this outside world? Specifically we may ask which concepts can be used, which attributes can be assigned to describe the outside world? We shall call such attributes "real" or "objective" quantities.

In Quantum Physics just as in classical Physics we talk about systems and processes. This means that we divide the world into small pieces to which we assign an indiduality. It is quite clear that this division procedure cannot be carried through arbitrarily and that it may have its limitations. Niels Bohr emphasized the indivisibility of certain processes as one of the essential lessons of Quantum Physics. If we go to the extreme and paraphrase this feature saying "the whole is more than the sum of its parts" then we have to admit that no system (apart from the whole universe) and no event can be completely "objective" because in isolating it, in assigning an indiduality to it we (subjectively) introduce some falsification of the real world. On the other hand it is evident that under suitable circumstances we can consider systems and events as real (objectively existing) individuals within a sufficient degree of approximation. We are thus lead to the approximate (or asymptotic) concept of "irreducible system" and "irreducible process". Let us make this more concrete in the example of Quantum Mechanics. There a system will be a collection of particles such that at the time under consideration the ties of this set of particles to the remainder of the world may be (practically) ignored. It may be called irreducible if, at this time, no subset of these particles may be considered as isolated from the others to the desired degree of approximation.

Thus, the notion of "system" (to which we can assign an individuality in an objective sense) will vary with time. We have so far used as the criterion for application of this notion large spatial separation from other bodies (relative to the range of forces) at a given time. Let us see whether this is sufficient to arrive at a reasonably complete, objective description of the outside world. According to this picture we have a decomposition of the outside world into "irreducible systems" existing at a particular time and "events" which correspond to collision processes between systems and lead in general to a change of the systems. The schematic picture of a (macroscopic) space-time region of the outside world is then a network in which the lines correspond to irreducible systems, the vertices to events. The direction arrows on the lines indicate the temporal sequence.

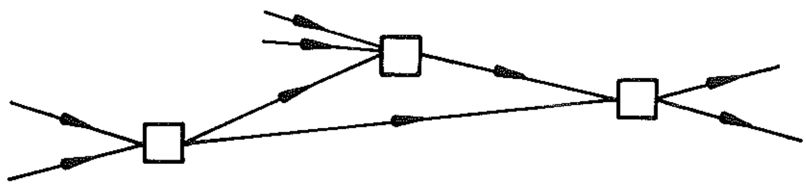

Fig. 1

In order to come from this picture to a reasonably complete description which satisfies our desire for (at least statistical) causality, the simplest assumptions would be

a) each system has attributes summarily denoted by ξ (its individual state).[3]
b) for a macroscopic system the wellknown macroscopic attributes (classical or thermodynamic state quantities) belong to ξ.
c) An individual event is characterized by a transition from an initial state $\xi_1, .. \xi_n$ (ξ_i being the individual state of the i'th incident system) to a final state $\xi'_1 ... \xi'_n$. Given the initial state the laws of nature determine the probability $W(\xi'_1 .. \xi'_n | \xi_1, .. \xi_n)$ for this event.

The theory would then have to classify possible types of systems and events, provide information about the set through which ξ may range for each type of system and determine the probabilities W for each type of event.

Let us see now, whether the above picture with the simple assumptions a), b), c) is in accordance with the laws of quantum physics. The answer will be: not entirely, but in important special circumstances yes. We discuss some characteristic examples first and shall then consider the necessary modifications of the above assumptions.

Example 1: Passage of Cosmic Radiation Through the Atmosphere

Here the simple scheme is adequate. The "systems" are single particles such as molecules in the air, protons, mesons etc. The events are binary collisions. The individual state of each particle is characterized by a momentum p and a spin wave function u (direction in a (2S+1) dimensional complex space). The probability $W(p_1' \, u_1'/p_1 \, u_1, \, p_2 \, u_2)$ is replaced by the differential cross section which is computed according to quantum physical laws for a single binary collision process. With this input and an ordinary stochastic treatment of our ignorance (including the averaging over all spin wave functions) we obtain a good description of the observed phenomena. Why do we know that each particle has a definite momentum though we may not know its value and we have not attempted to measure it? This comes from the circumstance that the spatial distance between subsequent events is large compared to the range of the interaction forces. Therefore, on the one hand (using now customary language of wave mechanics) a particle emanating from one event will have a wave function which is practically a plane wave within the subsequent interaction region. On the other hand the network will be practically always a "tree diagram" (no loops occur) so that "interference phenomena" between different branches of complicated multiparticle wave functions are excluded.

Comments: In spite of the special circumstances and in spite of the approximations used in the treatment, this example illustrates one very important and general aspect. The concept of an individual state for a (reasonably isolated) system is introduced for the purpose of separating the past history from the future fate of this system. We may consider each as a part of the network, the former consisting of those events which are reached from the line of the system under consideration by proceeding exclusively along lines in the opposite sense of the time arrow, the latter of those reached by following the lines in the direction of the arrow. The union of the two parts, of course, still does not give the whole connected part of the network. The method of theoretical description to which the assumptions a), c) above are geared is such that we envisage a class of networks in which the past history of one or several systems is fixed whereas the future parts vary. The essential simplifying feature in our example 1 lies in the fact that we do not have to envisage all possible future types of events but only a limited class of them. The limitation is not a subjective one, but arises from the (real) limitation in the types of systems which are available as collision partners. Corresponding to this limitation the parts of quantum mechanical wave functions belonging to far separated regions need no longer be regarded as members of one inseparable unit but may each be considered as individual entities describing mutually exclusive possibilities. In the statistical description of an ensemble of such processes this is the step of replacing the wave function by an incoherent mixture. It arises here not as the result of a planned measuring act but as a consequence of qualitative limitations in the possible types of reaction processes under the prevailing circumstances of the part of the outside world under consideration.

One may object that this argument - and hence the assignment of the individual state to each system - depends crucially on an approximation and that the realistic description is untenable if the process is treated really rigorously. However, one has to bear in mind that in all cases in which we carve out an individual element from a complex structure there is an approximation involved; very large quantitative differences become qualitative differences and in every area of science we are concerned with idealizations based on the disregard of absolute precision. If we wanted absolute precision we would also have to negate the existence of individual human beings and there would be no sense to our discussion.

Example 2: Einstein, Podolski and Rosen

This is the most transparent illustration of the fact that the simple assumptions a) and c) above have to be modified, i.e. that the spatial isolation at one time is not always enough to guarantee that a system has an objective individual state in the sense used in assumption c).

Let us consider the decay of a spin zero particle A into two charged spin $\frac{1}{2}$ particles B,C, which subsequently may interact with Stern-Gerlach magnetic fields S_i and ultimately with photographic phates P_i . The network corresponding to such a process is

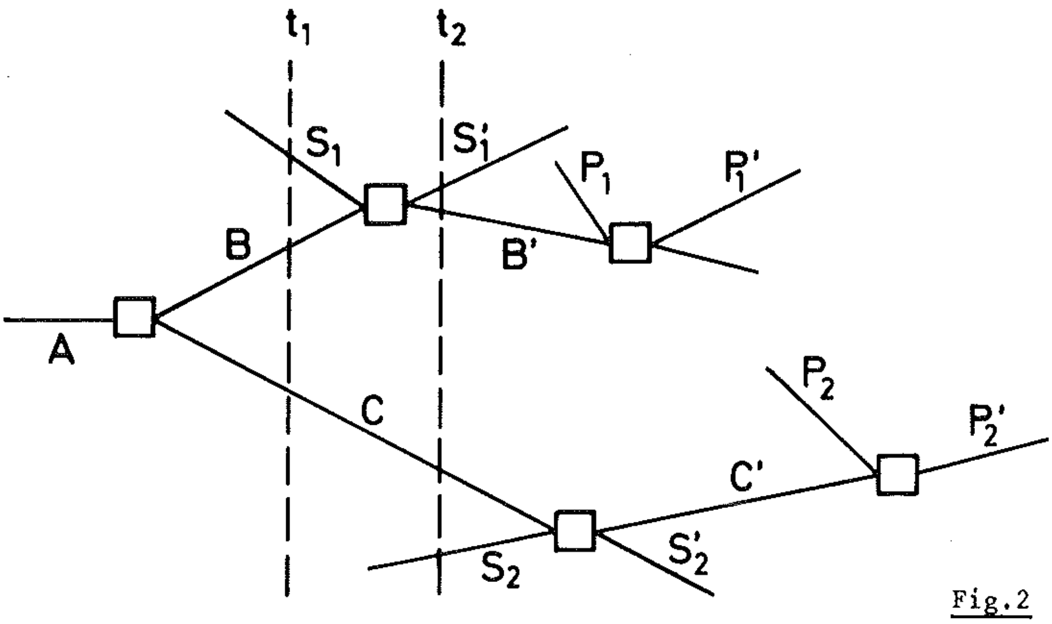

Fig.2

The magnets S_i are characterized by unit vectors $\vec{e}_i$ which give the direction of the inhomogeneous magnetic field; the plate P_i is so placed that it detects a particle if it is deflected from its original path in the directions $\vec{e}_i$ and it is not hit by a particle deflected in the $-\vec{e}_i$ direction. We have also indicated on Fig. 2 two time cuts, the first(time t_1) in which we have the practically isolated systems B and C before any interaction with a magnet; the second at t_2 where we have B' and C and B' has undergone a scattering process by the magnet S_1 whereas C has not interacted yet.

According to the quantum mechanical calculation the probability of obtaining a speck on both plates is given by

$$P(\vec{e}_2,\vec{e}_1) = \frac{1}{2} \sin^2 \frac{\theta}{2}$$

where θ is the angle between $\vec{e}_1$ and $\vec{e}_2$.

If the assumptions a) and c) were good for the first time cut then we should be able to write $P(\vec{e}_2,\vec{e}_1)$ in the form

$$P(\vec{e}_2,\vec{e}_1) = \sum_{\xi_1,\xi_2} F(\xi_1)\, G(\xi_2) \quad W(\vec{e}_1,\xi_1) \quad W(\vec{e}_2,\xi_2)$$

where F, G are probability distributions and W is a transition probability matrix. Such a decomposition of P is, however, impossible.[4)]

Therefore, in this example it is not possible to attribute individual states to the systems B and C separately at time t_1 although the criterion of large spatial separation is satisfied. The attribute of individual state at time t_1 can only be given to the combined system (B C).

The assumption a), b) c) have to be modified by replacing the word "system" everywhere by another concept which we might call an "irreducible complex". Such a complex may possible consist of several irreducible systems, coherent in spite of large spatial separation due to common past history.

In the course of time as the network grows there is a tendency of breaking up complexes (as well, of course, as the possibility of forming new ones). Thus in the example 2 we have at t_1 the irreducible complex (B,C) but already at t_2 the irreducible complexes are the systems B' and C separately. The coherence is broken by the same mechanism as described at the end of example 1. The magnet S_1 decomposes the total wave function into two disjoint parts with ultimately far separated support regions in configuration space so that no interference between them is possible in any practically attainable future event. Each of these two disjoint parts describes a definite spin state for B' and for C.

The Einstein-Podolsky-Rosen example demonstrates in the extreme the fact that the concept of an objective individual state is not always a causal one. Here the existence of a specific state for the system C emerges somewhere in the middle of the C-line as a consequence of an event which can have no causal influence on C. This disconcerting feature was encountered in a different and milder form already in the discussion at the end of example 1. Namely, the real individual state of a system (or complex) is not strictly a function of the past history. It becomes independent of the future only if some qualitative restrictions concerning future events are added. We must now say also that it is not always independent of events at space-like-distances. One may conclude from this that the concept of real, individual state should better be avoided altogether. I do not, at this moment , hold this opinion. However, be this as it may, the assumption of a real outside world and the possibility of describing it are not contradicted by the laws of quantum physics. The question is only how the outside world may be carved up into pieces to which one may still attribute an objective individuality and real attributes. Apart from its epistomological aspect this statement may even be useful to bear in mind for physics itself since it may be that at one time the selfconsistency between the available types of measuring apparatus and the dynamical laws becomes important.

Let me close this discussion with a very brief remark concerning the measuring process itself. Essentially it is assumption b) above which is relevant here. It is not an independent assumption but should be derived from the microscopic laws. This derivation is indeed a well known program which may be paraphrased as the "fundamental task of quantum statistical mechanics". While at present no complete and satisfactory solution of this task has been accomplished, there do exist partial results [5] which strongly indicate that indeed the assumption b) is a consequence of the microscopic quantum physical laws.

Footnotes

1) I believe that the answer is no for the following reason: The relevant experiments and observations may be automatized to the extent that the role of the human observer is reduced to sheer acts of cognition which do not alter the phenomena any more. Against this one may raise the following objection. It is sometimes argued that a rigirous application of the principles of Quantum Physics would lead to the conclusion that the speck on a photographic plate or even the number printed out by a computer can never be a fact but only a potentiality as long as nobody looks at them and that these things become facts only after the instruments have been read by an intelligent observer; in other words: the termination of the measurement is only in the mind. According to this claim Quantum Theory tells us that an unobserved photograph stored in my files has no pictures, and only when I look at the photograph then one of the potential pictures is created as factual. If this statement could be claimed to be an inescapable consequence of the laws of Quantum Physics then I personally, would conclude that there must be something fundamentally wrong in our understanding and application of these laws. However, I do not believe that this claim can be maintained and we shall return to this point below.

2) The assumption of an "outside world" does not touch the dispute between idealistic and realistic philosophies since we talk, after all only about a limited range of phenomena, the "physical universe" in the sense of the above abstraction.

3) To indicate the scope of possible candidates for ξ: it might be a collection of "hidden variables", it might be a wave function.

4) This is easily seen since $P(\vec{e},\vec{e}) = 0$ and since the three functions F, G and W should all be non negative.

5) See for instance the book by D. Ruelle "Statistical Mechanics, Rigorous Results" and the article by K. Hepp "Quantum Theory of Measurment and Macroscopic Observables", Zürich preprint 1972.