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On the Lessons of Quantum Physics

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Twenty years ago Klaus Hepp, partly together with Elliott Lieb, wrote a series of important papers on the theory of measurement and macroscopic observables in Quantum Theory. So on the occasion of his round birthday it may be appropriate to offer some ideas concerning aspects of the theory which may have a bearing on future developments. It is remarkable that the standard language (and conceptual structure) of Quantum Theory has withstood not only the severe criticism and expression of dissatisfaction in the long lasting disputes but also the enormous progress in physical knowledge and enlargement of the scope of problems addressed since 1930. We should, however, not be seduced by this to believe that this structure is so universal that it will remain the basis for any future theory. Rather I think that a fundamental future theory needs a different language and that for instance the concept of "observable" will not appear in it though essential lessons emphasized by Bohr do not loose their validity.

Two central problems at the advent of Quantum Mechanics were formulated by Bohr as "the impossibility of any sharp separation between the behavior of atomic objects and the interaction with the measuring instruments which serve to define the conditions under which the phenomena appear" and "the inability in ascribing conventional physical attributes to atomic objects". The consequences drawn involved a shift away from realism. Quantum Theory deals with the results of measurements not with conjectures about the properties of an outside world called nature as detached from the observer.

We must ask then: what are the essential features of an "observer"? Is it consciousness? Or action and participation by planning and conducting an experiment? Both have been argued but they do not provide a credible answer to the inabilities mentioned above. We can rule out the relevance of consciousness because the reliability of mental impressions in discussions among physicists is far below that of a document like a photograph, irrespective of the fact that mental impressions do constitute the primary source of our knowledge. The active participation does not seem to be relevant either. We want to apply Quantum Theory to processes in stars or in the early universe. The signals we receive from there are not of our making and the experiments planned to gain knowledge are very indirectly and only by a long chain of theoretical arguments related to the questions one wants to answer. Physics, by its very method, proceeds within an *as if* realism and Quantum Physics is no exception. The raw material are documented facts whose independence from any cognitive process of an observer may be safely assumed. It is the task of the theory to explain the relations between these facts. Thus Heisenberg concedes that a photographic plate may be regarded as an observer. One might then consider as the characteristic property of an observer the ability to produce a document or the closely related ability to produce macroscopic amplification allowing direct perception or documentation. But is the notion of "fact" synonymous to "document"? Is there clear evidence or is it only an exaggerated demand for caution which suggests that we must insist on macroscopic amplification as an essential defining property of a fact?

Let us look at a simple example illustrating the impossibilities mentioned above: the measurement of the position of an electron. Here the basic "element of reality" is a dot on a photographic plate or a flash from a scintillation screen. These are indeed no attributes of the electron. The reasonably sharp position in space *and in time* is an attribute of the *event*, i.e. the interaction process between the electron and molecules in the measuring device. Other experiences indicate that we cannot assume that the electron by itself has a position at a given time. The natural conclusion is that "position" is no attribute of the electron whereas space-time position is an attribute of a certain class of events. This suggests that the notion of event is a primary concept, in some sense more basic than that of an "atomic object". The latter (here the electron) appears in the role of a causal tie or link between two events (its birth in the electron source and its transmutation in the interaction with the measuring device). It suggests further that the relation to space-time is provided by the events, not by the atomic objects.

We must ask next whether the presence of millions of molecules providing the possibility of amplification by chain reaction is an essential ingredient in the notion of event or whether it is legitimate to consider the dissociation of a single molecule caused by the electron and starting the chain reaction already as an event. This addresses the division problem. Strictly speaking it is – at least in the existing theory – impossible to define either a physical system or an individual event as detached from its environment. Whether we speak of electrons and atoms or of events and processes there is always some idealization involved whose worth depends on the possibility of approaching the idealized situation. In complex phenomena it demands an ordering according to relevance of simplifying assumptions. In this sense the division of complex events into a sequence of (more) elementary ones has the same status as the division of bulk matter into atoms. The fact that this divisibility has a limit, i.e. that there exist discrete structures (stable particles and indivisible events) is one basic feature distinguishing Quantum Physics from Classical Physics. Qualitatively this has already been pointed out by Bohr in his emphasis on the "indivisibility of a quantum Process". From a more elaborate discussion of this question[1] it appears that macroscopic amplification is not the essential precondition for the notion of event. It would be very unnatural to maintain that the multiparticle production in a high energy experiment is tied to the presence of detectors or that such events do not occur in the collisions between cosmic ray particles and molecules in the air irrespective of any registration or planning. The idealization involved in speaking about the event of a *p-p* collision depends on the energy transfer and, in the lower energy regime, on the isolation, not on the amplification. In other words the concept of event is more general than that of a document.

This is of crucial importance because it demands a revision of a widely held dogma. An event is a fact and irreversibility is inherent in this concept. According to widespread belief the fundamental laws are time-reversal invariant and irreversibility appears only on the macroscopic level due to a coarse grained description. This should be seriously reconsidered in Quantum Physics. My criticism does not refer to the TCP-invariance of the dynamical laws in Quantum Field Theory but in the relation of individual phenomena to these laws. The indeterminism of Quantum Physics together with the discreteness of individual effects implies that the dynamical laws refer to statistical ensembles and that the realization of a discrete effect from a large number of possibilities is a *decision* which is neither taken by the observer nor described by the dynamical law for the wave function, statistical matrix or observables. The effective decoherence for collective coordinates (which may be idealized by the appearance of superselection rules in the limit) is an important aspect in the measurement problem showing the effective transition from a pure state of the observed system to a mixture. It does, however, not touch the decision present in the individual case. This is an additional, independent law in Quantum Physics where irreversibility comes in. Apart from the necessary differentiation between the description of ensembles and the individual behavior it may be worth while to point out that coarse graining alone can never produce an asymmetry in the time direction. It is well known that in addition one needs "natural assumptions" about the initial conditions which are not natural conditions for the final situation. According to present knowledge the arrow of time is equal (by continuous transport) in all accessible parts of the universe. We may leave it open whether the reason for this should be sought in cosmology, specifically in the expansion of the universe. If so, then Quantum Physics including all its applications is shaped by cosmology. The opposite point of view, that cosmology is shaped by quantum physics might also be envisaged.

Leaving aside such speculations we can assert that as soon as we accept the existence of discrete facts independent of the cognition by an observer we are forced to an evolutionary picture where in the progress of time new events are realized and the events are connected by directed causal ties which, in the simplest case, are particles and where ultimately space-time is related to the pattern of events[1]. Such a picture appears very natural. The development of a theory based on it is, however, no small task.

[1]R. Haag, An evolutionary picture for quantum physics, Commun. Math. Phys. to appear 1996, and Local Quantum Physics, second ed. Chapter VII, Springer 1996.