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On Some Consequences of the Breakdown of Counterfactual Definiteness in the Quantum World

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The crucial role of counterfactual reasoning in generating inconsistencies between local subquantum theories and quantum mechanics is stressed. It is argued that the physical justification of such reasoning requires the fulfilment of a criterion of actualizability of hypothetical situations. It is demonstrated that in a subquantum framework this criterion is equivalent to the assumption of actual reproducibility of individual subquantum states. Therefore, inconsistencies between local subquantum theories and quantum mechanics disappear if a nonreproducibility property of nature, in full agreement with the empirical fact that past, present and future are basically distinct, is invoked. The proposal also leaves the universal validity of the locality principle untouched, in agreement with all existing empirical evidence.

1. Introduction

Counterfactual reasoning deals with hypothetical processes that could have happened in the past or still may happen in the future. The assumption that hypothetical processes obey the same laws as actual processes and, hence, lead to definite outcomes is usually called counterfactual definiteness (CFD). The frequent and successful use of CFD in most branches of physics has, apparently, given rise to the impression that it is generally valid.

It seems, however, that in the field of the foundations of quantum mechanics (QM) counterfactual reasoning is at the basis of a number of results which contradict quantummechanical predictions [1, 2, 3]. These results originated from the argumentation of Einstein-Podolsky-Rosen (EPR) [4] (arguing against the completeness of QM), from Bell's "proof" of the nonlocality of QM [5], and recently from counterfactual inferences from the Aharonov-Bergmann-Lebowitz (ABL)-rule [6, 7, 8]. During the last decades these studies have been further developed [9, 2] and alternatives [10, 11] have appeared.

Because the relevant quantummechanical predictions are all empirically verified it seems necessary to investigate how far counterfactual reasoning in physics is reliable and whether it is always used in a justifiable way. This will be done in Sect. 2 where the conditions for a justified counterfactual reasoning are summarized. Application of these conditions to hidden variable theories and to inferences from counterfactual application of the ABL-rule are discussed in Sect. 3. It is concluded that an appropriate use of CFD removes all quantum contradictions. It is argued that in hidden variable theory (HVT) this amounts to a nonreproducibility of individual quantum situations, in full agreement with the empirical fact that past, present and future are basically distinct.

2. Criteria for a justified use of CFD

2.1 Availability of a theory

In classical mechanics (CM) and standard QM counterfactual reasoning is unproblematic because these theories represent physical situations which have the property of being reproducible, i.e. the preparation procedure may be repeated to give rise to physical situations which are represented by identical states. The essential point here is that some theory is available for allowing *quantitative* argumentations.

In the field of the foundations of QM this point is often overlooked, e.g. when one tries to recover the standard QM from considerations on *individual* quantun events. In many cases, e.g. in STAPP's recent nonlocality-of-QM argumentations [12], it is claimed that neither supplementary (or hidden) variables nor a corresponding dynamical formalism (obeying some properties such as locality and validity of CFD) are needed for carying through the proof.

However, consistency then requires that one should refrain from making any quantitative argumentation (in particular counterfactual ones) in which individual quantum events appear. Only considerations on *ensembles* of individual quantum events (for which a theory, QM, exists) do have physical relevance. Counterfactual statements should then, at best, concern only such ensembles and never the individual members themselves. Hence, if individual quantum events are considered (as is always done in the nonlocality issue) then the existence and the introduction of so-called hidden-variables (HVs) λ are implicitly assumed as characterizations of more detailed physical situations, the significance of λ being left entirely to the imagination of the theorist.

2.2 Verifiability

Physical relevance of argumentations based on some formal scheme is, furthermore, connected with the fulfilment of a criterion of verifiability: for given initial conditions the theory gives only one specific prediction. This implies that physical theories should have the property of *formal determinism*. Both CM and QM have this property, CM applying to *individual* classical events and QM applying to the statistics of measurements on *ensembles* of single quantum events. It is obvious that the property of formal determinism also determines the theory's domain of applicability which does not necessarily coincide with its domain of validity (e.g. CM does not apply to individual *quantum* cases).

Finally, applied to possible subquantum hidden−variables theories (HVTs) for individual quantum processes, the criterion of verifiability requires the new theory to be also of the deterministic type. In such a HVT individual quantum preparations should allow then to make predictions with certainty for that specific observable. The lawful behaviour of ensembles of individual quantum events (i.e. QM) suggests strongly that also the individual events themselves proceed according to definite laws. Moreover, the existence of predictions with certainty in cases of perfect correlation and our arguments in favour of locality (see Sect. 3.1) suggest that these laws be of the deterministic type, as required by our criterion of verifiability.

2.3 Actualizability

When entertaining counterfactual reasoning one usually does not bother about the realizability of the theoretically allowed possibilities for the initial conditions. Yet actualizability of hypothetical situations is crucial. If for some reason some particular situation can never be realized then any counterfactual statement about it is completely irrelevant. So physical relevance demands that the assumptions (such as CFD) which underly physical argumentations using some theoretical scheme not only are *theoretically* allowed but they must also correspond with *actualizable* physical situations.

One should be well aware here of the fact that such a guarantee for actualizability cannot come from the allowance by the theory of a particular situation as a theoretical possibility, but can come only from actual experience. Such an actualizability or reproducibility hypothesis (RH) would justify then not only the use of CFD but also the assumption that counterfactually considered processes obey the same rules as actual processes.

Conversely, indications for the impossibility of the actualizability of a theoretically allowed possibility (and of the invalidity of the corresponding counterfactual reasoning) can be decided on the ground of inconsistencies (e.g. with QM) arrived at. Hence, it may be envisaged that restricting the justified use of CFD in a particular domain is one of the possibilities to resolve inconsistencies ensuing from physical argumentations. It follows that the physical ground for a possible invalidity of CFD is that a reproducibility hypothesis (RH) concerning a former actual situation is not fulfilled.

3. Some consequences of the requirement for a justified use of CFD

3.1 Hidden variable theories

As is well known it is not CFD that is sanctioned for leading to the inconsistencies between local HVT and QM but instead it is almost generally agreed (at least by those working in the field) that causality and locality (LOC) are basically violated by QM (although the predictions of QM in its domain of applicability, i.e. for ensembles, are perfectly local [13]).

This nonlocality inference is very strange and unacceptable because causality and locality are at the very basis of modern physics and of all successful theories for e.g. the behaviour of elementary particles. When asked for their opinion elementary particle physicists will unanimously reply that causality and locality will be the last principles that will be given up in physics. Of course, there is another very good reason for this firm standpoint because these principles are supported by existing empirical data. Therefore it is incomprehensible that, apart from a few exceptions [14, 2]), the general validity of CFD has never been questioned. Yet H. P. Stapp [15] seems to be clearly aware of the point: after acknowledging the crucial importance of the CFD assumption ("The key operative concept of the EPR-Bell argument is … counterfactual definiteness.") he states that "No satisfactory derivation of nonlocality, or the existence of faster-than-light influences, can be based upon such a CFD assumption: a failure of this assumption is … far more likely than the existence of a faster-than-light inluence". However, in his later "proofs" Stapp has always argued that locality is the only explicit assumption and claims that these proofs are independent of any other implicit assumption such as CFD. For reasons given above we have argued frequently [2, 3] against this approach which denies clear and unambiguous empirical evidence in favour of LOC.

As opposed to Stapp's approach we argue as follows. In order to get the known quantum "paradoxes" in general counterfactual considerations have to be made on *individual* quantum processes. From our actualizability criterion of Sect. 2 it follows that the justification of such reasoning rests on the assumption that a state λ in some HVT must have the property of being reproducible in the future. Hence, we conclude that the paradoxes may be removed by setting limits to the *justified use* of CFD in the domain of individual quantum phenomena which amounts to accepting a basic *nonreproducibility property* of nature at the individual quantum level. The compatibility between a breakdown of CFD or RH at that level and the validity of CFD and RH at the level of standard QM (i.e. the fact that quantum ensembles and the statistical predictions for them may be reproduced) is explained mathematically by Kupczynski [16] in terms of Pitowsky's model [17] of sets of measure zero.

After all the breakdown of CFD is not surprising because in principle the *exact* representation of a measurement result should require an *infinite* number of digits. From the domain of applicability of our existing theories, CM and QM, one might say that apparently that part of experience which is rather insensitive to such an exact representation is described by CM, whereas the other part, described by QM is more sensitive to an exact representation. The violation of BI by QM seems, then, to indicate a further restriction because exact representations cannot be duplicated or copied. Also, if the activities which are covered by physical theories are restricted to reproducible phenomena (in the sense that their reproduction is represented by identical states) then our results give some support to Bohr's claim that QM is complete, at least from the point of view of a human observer or, in Bell's terminology, in a FAPP sense, i.e. "for all practical purposes".

3.2 The ABL-rule and its counterfactual applications

It is only recently, in conjunction with some controversies with respect to the counterfactual interpretation of the Aharonov-Bergmann-Lebowitz (ABL)-rule [6] that the criticism related to the validity of CFD in QM has been taken more seriously. The ABL-rule concerns probabilities of events in quantum ensembles which are defined by pre- and post-selection. The counterfactual interpretation has been developed by Aharonov, Albert and Vaidman [7, 18, 8].

Originally the ABL-rule concerns the probability of outcomes of *actual* measurements and is a direct result of the basic rules of QM. Therefore, if only *actual* events are considered no results derived from the ABL-rule may be termed more "surprising" than other quantummechanical results. The qualification "surprising results" of QM [7, 8] originated only in recent years when a counterfactual interpretation of the ABL-rule was used and inferences were made for results of measurements which "could have been done but were not". In this way Aharonov and collaborators claimed that the behaviour of quantummechanical systems in the interval between two actual measurements (i.e. for so-called pre- and post-selected systems) is surprising because incompatible observables would have definite values in that interval. However, because of the quantummechanical impossibility of measuring incompatible observables in one single actual measurement the inference of the values of such incompatible observables can only have a physically justified meaning when equivalent but different ensembles are considered. Hence, only part of the information gained by a counterfactual interpretation of the ABL-rule is useful for prediction of *future* results. It is precisely this part of the information that is needed in standard QM for making the same predictions. Because the other part of the information is irrelevant for future results, it may be termed irrelevant and superfluous. Also, if by using such information one should get results which contradict QM then this is insignificant because the contradiction cannot be brought to the observational level. Of course, it may also happen that incorrect use is made of the ABL-rule [19, 20].

3.3 Do unperformed experiments have results?

From our discussion in Sect. 2 we may conclude that Peres' statement that "Unperformed measurements have no result" is strictly correct but when our criteria for the justified use of CFD are fulfilled then it is yet possible to consider safely the results of unperformed measurements.

4. Conclusion

In summary, counterfactual reasoning in some domain is justified provided it may be assumed that a theory for the relevant processes exists and that the physical situations it describes are reproducible in the sense that they are representable by identical states. If this should not correspond with reality then a number of situations may exist for which paradoxical results may be derived. A picture in terms of nonreproducible situations at the subquantum level should provide, then, an explanation for the apparent "nonlocality" in various correlated situations (of the EPR-Bell-type) and for the phenomenon of contextuality in a number of other situations (of the KS-type).

By studying the conditions for a physically justified use of CFD we have come to the conclusion that within a HV framework a physical reproducibility hypothesis, RH, concerning the reproducibility of individual quantum situations (such that these may be represented by identical HV states) must be fulfilled. It is concluded that these paradoxes may be resolved by assuming a *nonreproducibility property* at the individual subquantum level.

We have argued that when the counterfactual interpretation of the ABL-rule is subjected to the criteria for justified use of CFD, in particularly verifiability and actualizability, then all surprising quantummechanical results disappear or become results of standard QM.

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