QUANTUM NONLOCALITY WITHOUT COUNTERFACTUAL DEFINITENESS?

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Stapp's recent proof of the nonlocality of quantum mechanics is critically discussed. It is demonstrated that in his derivation of the Bell inequalities an extra requirement, over locality, is used, which is tantamount to counterfactual definiteness, and that is not a consequence of locality.

Keywords: quantum mechanics, hidden-variables theory, Bell inequalities, locality, counterfactual definiteness, reproducibility.

1. INTRODUCTION

In his recent publications[1,2] Stapp tries to prove the non-locality of quantum mechanics without the assumption that measurement results of unperformed measurements exist, i.e., without the presupposition of counterfactual definiteness (CFD). In earlier work[3], employing CFD he was able to prove that, for measurements of the Einstein–Podolsky–Rosen (EPR) type, the Bell inequalities (BI) should necessarily be fulfilled. This proof was essentially based on the existence of quartets of measurement results, only two of which being actually measured, whereas the other two are counterfactually fixed "within nature" (to be obtained experimentally if the other measurements would be performed). As Stapp remarks, however, the idea of CFD, in which the existence (independently of measurement) is assumed of a value of every observable (to be reproduced faithfully if the measurement of the observable is performed) is "definitely contrary to orthodox quantum thinking"[2] and "probably [a] false concept." Hence, a derivation of the BI from CFD is not very relevant to the orthodox quantum physicist.

It is Stapp's contention that also *without* CFD it is possible to derive the BI and hence a contradiction with quantum mechanics. Since, according to Stapp, the only assumption that must be made, is the assumption of locality, his conclusion is that quantum mechanics is not compatible with locality.

In this article we want to perform a critical examination of Stapp's reasoning, and demonstrate that his conclusion is not warranted, either from the point of view he used to defend earlier[3], viz., the view that the incompatibility between quantum theory and the BI holds independently of the question of realism, objective reality, and hidden variables, or from his present position. In the following it will be argued that in his recent work[1,2] an element of objective realism has slipped in which can be held responsible for the derivability of the BI. We shall demonstrate that without this element the derivation breaks down. We also give reasons why we think that quantum mechanics does not describe *objective* reality.

2. STAPP'S RECENT PROOF

Let us first give a short account of the main characteristics of Stapp's recent argumentation and, for simplicity, use thereby the notation of Ref. 2. Stapp considers the EPR situation of two spin–1/2 systems prepared in the singlet state. It is assumed that two batches of N such correlated systems enter two spacetime regions R_A and R_B that are causally disjoint. In each of these regions an observer chooses between measuring two different (incompatible) observables, M_i^A, $i = 1, 2$ and M_j^B, $j = 1, 2$, respectively. Hence, for this single set–up it is possible to consider, in a theoretical analysis, four possible EPR measurements with pairs of results $(x_{ik}, y_{jk}), k = 1, \ldots, N$ for the pairs of observables (M_i^A, M_j^B), $i, j = 1, 2$; $x_{ik}(y_{jk})$ equals the kth entry in the ordered sequence of N measurement results of the observable $M_i^A(M_j^B)$. In the following these sequences will be denoted by x_i, y_j. Also, N is supposed so large that the relative frequencies in the sequences are stable.

Stapp's argumentation, then, is based upon the following premises:

1. Free Choice: The choice of the experimenters in R_A and R_B can be treated as two independent free variables.
2. Unique Results (UR): When the observables (M_i^A, M_j^B) for a certain value of the pair i, j are measured *actually*, then nature selects (via some definite, but as yet unknown, mechanism, possibly to be incorporated in a more general theory than QM) in a unique way the results (x_i, y_j). In order to avoid his former use of the CFD assumption for proving the nonlocality of QM, Stapp's new argumentation uses measurement results only in this sense. With the assumption UR there is no question of attributing measurement results to the other (unperformed) experiments. Yet, under the supposition of the possibility of the repeatability of the same *actual* individual preparation, it is possible to *contemplate* the situation that for a specific preparation another choice for the pair i, j of measurements is made. Under this condition, then, it is possible to consider for each individual preparation act four possible measurement results (x_i, y_j), $i, j = 1, 2$, each pair being obtained as the unique *actual* result if the corresponding measurement (M_i^A, M_j^B) is performed. Each such

pair is also a possible pair in a *future* experiment.
3. Validity of QT for each of these four sequences. Hence it is also required that the predictions from any more general theory should be compatible with the predictions by QT.
4. Locality principle LOC: "For all that pertains to the generation of a measurement performed in R_A the choice made by the experimenter in R_B can be considered not to exist, and for all that pertains to the generation of the result of a measurement performed in R_B the choice made by the experimenter in R_A can be considered not to exist."

Because of this locality condition the localized physical processes leading to each measurement result, i.e., its generation, must be independent of which measurement is performed in the causally disjoint region. It follows that if this generation of measurement results can be repeated or reproduced in *different* experiments, we may infer the equality of the results themselves; that is, if x_1 and x_1' are sequences of measurement results for M_1^A, obtained in measurements of the pairs (M_1^A, M_1^B) and (M_1^A, M_2^B), respectively, then it is possible that $x_1 = x_1'$. With the crucial implicit assumption of reproducibility there is also no objection to consider such equalities in a theoretical analysis of a single experiment as is done by Stapp.

On the basis of his condition LOC Stapp proves the validity of the following intermediary properties: Property A': "There exists a pair (x_1, x_2) such that Nature could, if $i = 1$, produce in R_A the result x_1, independently of j, and, if $i = 2$, produce in R_A the result x_2, independently of j.", and an analogous Property B' with respect to a pair (y_1, y_2) of observations which could be made in R_B.

In his argumentation, Stapp requires further that *both* properties A' and B' be valid *conjunctively*, which implies the existence of a quartet (x_1, x_2, y_1, y_2) of possible measurement results for a specific (sequence of) preparation(s). This quartet should have the important property that the pair (x_i, y_j), extracted from this quartet, is a possible pair of measurement sequences in the measurement (M_i^A, M_j^B), $i, j = 1, 2$. This would amount to the possibility of matching these four measurement sequences in such a way that the mean values $(1/N)\sum_{k=1}^{N} x_{ik}y_{jk}$ of the quartet are possible (approximations of the) expectation values $< M_i^A M_j^B >$ obtained in the

EPR correlation measurements. These are demonstrated by Stapp to satisfy the BI, from which he draws his conclusion that, for the situation described above, the predictions by quantum theory violate explicitly Einstein's locality principle, which constrains the propagation of causal influences to lie within the light cone.

Note that Stapp's result is appreciably weaker than the one he obtained earlier by means of CFD. It is no longer necessary that (given a quantum mechanical preparation) *every* set of EPR measurements should satisfy the BI. However, if nature is local, according to Stapp it should *allow* that *some* of these do satisfy the BI. If this is never experimentally realized (as is, for instance, with overwhelming probability, the case for the singlet state of the two spin–1/2 systems for certain choices of spin components), then we must conclude that some mechanism prevents this possibility from being experimentally realized. Since, according to Stapp, no other elements have been introduced into the derivation than sequences of possible measurement results and the presupposition of locality, it can only be this latter assumption that fails. His conclusion is that locality is incompatible with the quantum mechanical formalism.

3. DISCUSSION OF STAPP'S RECENT PROOF

Stapp's analysis is essentially a logical analysis of the mathematical structure of possible physical theories. The logical schema used by him is the implication

locality $\rightarrow$ BI

or

violation of BI $\rightarrow$ violation of locality.

If the locality assumption would be the *only* assumption, then Stapp's conclusion would be irreproachable. However, it is extremely difficult to be sure that no extra assumptions are made that, instead of the locality assumption, could be the cause of the BI being satisfied. In Stapp's approach one extra (implicit) assumption is conspicuous, viz., the assumption that the measurement outcomes of all of the four measurements can be referred to the *same* individual preparation procedure. From an objectivistic point of view this implies a conditionalization of the measurement results on the (same) initial state of the object system. It is this extra assumption which allows Stapp to combine in his theoretical analysis four alternative possible situations (of which only one can be actualized at one time, while the other three remain hypothetical, but possible) without the need to introduce CFD in the way he did in his former version[3] of Bell's theorem.

Such a conditionalization is common practice on the *statistical* level of quantum mechanical measurement results[4] (the same state vector ψ represents identical preparations of, say, a batch of particles). However, extending such a conditionalization to the level of *individual* measurement results requires a new context in which identical *individual* preparations of a sequence of object systems are such that *each of them* is represented by the same initial state ϕ, which may be completely different from the QM state vector ψ (although we allow for the possibility that the quantum mechanical state ψ itself is taken for the description of an *individual* object, as is done in certain realist interpretations of quantum mechanics; for clarity also in this case we will in the following indicate the state of the individual object by ϕ).

The essential point of such a conditionalization is the existence of conditional probabilities $p(x_i \mid \phi)$ and $p(y_j \mid \phi)$ (for maximal generality we only consider statistical theories), attributing the probabilities of the observables (in deterministic theories even their values) to the initial state ϕ of the object. We call this the *objectivity assumption*, because of the supposition that the state ϕ describes the objective reality of the object *prior* to and *independent* of the measurement.

Actually, the attribution of an objectively defined state to the object, determined independently of the measuring apparatus, was held by Einstein to be a highly desirable feature of any physical theory, and the EPR thought experiment was precisely intended to probe such an objectivistic interpretation of quantum mechanics by studying a situation in which interaction between object and measuring instrument is avoided.

Any reasoning which starts from such a new context may leave the domain of orthodox QM reasoning and as such may proceed in various directions, keeping in mind, however, as much as possible the succesful insights of the standard view. In this respect we want to remark that the objectivity assumption is as alien to orthodox quantum thinking as is CFD, the inseparability of object and measuring instrument in the quantum measurement phenomenon being one of the leading principles of quantum measurement theory, which started mainly from Bohr's insights. In particular, he took the view that, within the domain of quantum mechanics "the unavoidable interaction between the objects and the measuring instruments sets an absolute limit to the possibility of speaking of a behaviour of atomic objects which is independent of the means of observation."[5] It seems to us that every theory, purporting to describe quantum measurements, must allow for Bohr's feature of wholeness. This implies that it is unwarranted to take for granted that the individual object can be prepared in the *same* individual initial state ϕ if *incompatible* observables are measured.

Contrary to Bohr's views, we might try to perform the following analysis of the EPR measurements. Assume the existence of conditional probabilities as defined above. Then we can also define a conditional joint probability according to

$$p(x_1, x_2, y_1, y_2 \mid \phi) = p(x_1 \mid \phi)p(x_2 \mid \phi)p(y_1 \mid \phi)p(y_2 \mid \phi).$$

By marginalization we can obtain from this expression the conditional probabilities used in socalled objective local theories[6], and derive the BI. It must be stressed, however, that in this reasoning the locality assumption is not essential. As a matter of fact, the BI are satisfied by *any* objective theory encompassing conditional joint probabilities $p(x_1, x_2, y_1, y_2 \mid \phi)$, either satisfying the relation given above or not[7]. We should bear in mind that, apart from the locality assumption, in these derivations the objectivity assumption is always presupposed. Hence, the logical schema employed by Stapp should at least be extended according to

objectivity + locality $\rightarrow$ BI.

This implies the possibility that quantum mechanics is compatible with locality, but does not describe an *objective* reality. Note that this does not at all mean that quantum mechanics is at variance with the *existence* of an objective reality, an interpretation often ascribed to Einstein. It only means that a description of such an objective reality requires a theory different from quantum mechanics, thus demonstrating the incompleteness of the latter theory. Indeed, if Bohr is right, the reality described by quantum mechanics is the reality of an inseparable whole of object and measuring instrument. Any attempt to separate the two, such as the one performed by Stapp, may lead us outside the domain of quantum mechanics.

We have no reason to believe that Stapp's results should be attributed to locality rather than to the presupposition, implicit in the objectivity assumption, that quantum mechanics refers to an objective reality.

Analogous remarks hold with respect to CFD. Stapp's *conclusion* to the existence of a quartet of measurement results is similar to his former *introduction* of CFD as a necessary assumption, in the sense that it is possible to attribute values for incompatible observables to an individually prepared state of the object, to be obtained if the measurement is performed. Also, this is completely in line with his assumption UR. Since Stapp claims that the existence of a quartet follows in an unavoidable way from his locality assumption LOC, it would seem that CFD in the above sense is a consequence of locality. However, as explained above, the possibility of a quartet should in the first place be seen as a consequence of the objectivity assumption, and is already implied by the existence of the more general "nonlocal" conditional probability $p(x_1, x_2, y_1, y_2 \mid \phi)$. For this reason the objectivity assumption may be seen as another form of the presupposition of counterfactual definiteness.

It is the objectivity assumption that makes it possible to assume the same initial state in different EPR experiments. Although the locality assumption is a natural one for the EPR situation, it is not necessary for a derivation of the BI. Objectivity and locality are taken as independent presuppositions, rather than one being derived from the other.

4. EXPERIMENTAL RELEVANCE OF STAPP'S REASONING

According to Stapp[8], his recent argumentation should be considered as an investigation of the logico-mathematical structure of the class of theories that encompass the domain of atomic physics, where the present quantum formalism gives correct results, and may be extended outside this domain. In order to clarify as precisely as possible what this means for Stapp, we find it opportune to quote again from him[8]: "Quantum theory makes *predictions* about what will happen in all four alternative possible measurement situations, even though only one of the four alternative possible measurements can actually be realized. Thus, as far as the mathematical structure of the *theory* is concerned, we *must consider*, when considering the structure of theories that reproduce *all* the statistical predictions of quantum theory, all four predictions simultaneously. For all four predictions are given simultaneously by quantum theory: They are all simultaneously a part of the mathematical structure of the theory.".

We have the following comments on this point of view. To begin with, we want to call attention once more to the obvious and trivial fact that, when QM makes predictions for theoretically possible experiments, one should all the time keep in mind that, for the *verification* of these predictions, *actual* observations have to be introduced in any relation which is the result of some argumentation. Now, from the way Stapp develops his argumentation, it appears that Stapp completely overlooks this crucial point: Indeed, nowhere there is any mention as to how real and *actual* measurement results are to be used to verify his derivation of the BI (based on his conclusion to the existence of a quartet of values). Nevertheless, on several occasions Stapp emphasizes that, with respect to his four possibilities (corresponding to the four choices by the observers), only one possibility can be actualized at the same time. As an immediate consequence, it follows that the measurement sequences of the quartet cannot all be obtained in the *same* measurement, even when Stapp considers them *simultaneously* in his theoretical considerations. Hence, in the final end, in order to obtain a quartet having empirical relevance, measurement sequences obtained in *different* experiments should be matched in some way. In other words, Stapp's theoretical alternative possibilities should *at least* correspond to *actually realizable* physical situations. As far as the *statistical* predictions are concerned, this requirement applies perfectly to the quantum formalism: Every alternative situation corresponds to a realizable situation. However, in more general theories which encompass QT and which could apply to *individual* situations, the requirement that theoretical possibilities correspond to actual situations is an *extra* condition which should be imposed. The question is whether it is possible to prepare the object in the *same* individual initial state ϕ in two incompatible measurements. Overlooking this crucial point would again amount to the adherence to the idea of CFD mentioned above and violate Stapp's UR assumption.

As stated before, Stapp's theoretical measurement sequences for the four alternative possibilities are to be identified, finally, with *actual* measurement sequences. This is the only physically relevant way for considering theoretical possibilities. From this point of view, then, there may not exist a logical difference between Stapp's theoretical sets of sequences (x_i, y_j) and sequences (x_i, y_j) of actual results, if Stapp's quartets are not to be reduced to mere logical structures of the theory without any empirical import. For this reason we shall in the following restrict our attention to measurement sequences that can be considered at least as possible sequences of *actually* performed experiments. By taking this more instrumentalistic position, we seem to be closer to Stapp's earlier point of view, referred to in the Introduction.

Let us examine the significance of Stapp's locality condition LOC from this point of view. To be more specific, let x_i, $i = 1, 2$ be an ordered sequence of measurement results of M_i^A, and, analogously, y_j for M_j^B, $j = 1, 2$. The assumption of locality implies that the sequence x_1, say, will not be influenced by the choice M_1^B or M_2^B. Hence, a given sequence x_1 of M_1^A may be a *possible* sequence in both EPR measurements (M_1^A, M_1^B) and (M_1^A, M_2^B). However, the locality condition does not imply that in any couple of EPR measurements (M_1^A, M_1^B) and (M_1^A, M_2^B) the x_1 sequences are the same.

It should be noted also that Stapp's locality condition cannot be verified unless further assumptions are made. Indeed, Stapp's formulation of LOC deals only with one single set–up, and it is seen immediately that experimental verification of Stapp's LOC presupposes a kind of reproducibility: In order to be able to verify that a measurement result in R_A is independent of the choice made in R_B, we would have to reproduce exactly the individual state ϕ of the object. Hence, in order to obtain Stapp's quartets, measurement sequences obtained in *different* experiments, but corresponding with the same sequence of individual state preparations, should be matched.

In actual experiments of the EPR type, we need four different experiments measuring EPR correlations in order to test the BI. In the following we shall approach Stapp's problem from this latter angle, in order to see to what extent Stapp's reasoning can be maintained if we do *not* require from the outset that the object can be prepared the same in incompatible measurements. We then would have to *demonstrate* that it is possible to have two identical sequences of individual preparations of the object system in two measurement sequences of incompatible observables. The result of this, not surprisingly, will be that this is not always possible within the domain of quantum mechanics.

If we want to consider Stapp's single preparation set–up from the empirical point of view embodied by the usual way in which the BI are tested by means of EPR–like experiments measuring two observables at a time, then we are confronted with the problem that the probability of ever obtaining the same sequence of microscopic preparations in two different EPR–like experiments is effectively zero. So, even if we would obtain the same sequences of measurement results (e.g. $x_i = x'_i$) in two different experiments, this would not necessarily imply the same sequence of state preparations.

However, if it comes to empirically testing the existence of quartets of measurement results by means of EPR–like experiments, we can follow a different strategy. If it would be impossible to obtain such quartets under a certain set of conditions, then such quartets would remain impossible if other conditions would be added to this set. Now we can take for the above mentioned set of conditions only those that are directly observable. We shall demonstrate that, under such conditions, the quantum mechanical description of EPR–like experiments does not universally allow the existence of quartets, independently of whether they correspond with equal or different sequences of state preparations.

For the set of directly observable conditions identifying a sequence of measurement results we can take, in the first place, the macroscopic parameters defining the states of the preparation and measurement apparata. Furthermore, it is reasonable to include the statistical data of the sequence of measurement outcomes, which must be the same in order that two sequences can be identified for the purpose of forming a quartet. From an operational point of view it would, even under these relaxed conditions, be very improbable that we could find two identical sequences, if we take into account different orderings of measurement results in sequences having the same statistical data. We can, however, appreciably increase the probability of finding identical sequences of N measurement results, by identifying sequences that are equal up to a permutation of their elements. This would not obviate the purpose it is used for, because we have no reason to assume that any permutation of a sequence of state preparations would be less possible than the original one. Now, having two identical sequences of measurement results does of course not guarantee that also the sequences of state preparations are identical. We, however, shall not be bothered by this, because for Stapp's reasoning it is sufficient that the latter sequences have a *possibility* to be identical.

5. HOW TO CONSTRUCT QUARTETS FROM DIFFERENT EPR MEASUREMENTS?

In Ref. 1 Stapp introduces a random variable λ (to be distinguished carefully from Bell's hidden variable) that seems to be instrumental in the matching problem, in which sequences of measurement results of different EPR measurements are matched in order to construct a quartet. Let us, however, for the moment ignore this random variable and follow Ref. 2, where this random variable is not explicitly introduced.

The question, then, is whether, given a large number of EPR measurement sequences $(x_i, y_j), i, j = 1, 2$, it must be possible, because of locality, to match some of these into a quartet. Referring to Sec. 3, where we discussed Stapp's recent nonlocality argumentation, it is not hard to see that locality *alone* cannot be a sufficient reason for requiring the possibility of the existence of such a quartet. In order to demonstrate this further, we start from Stapp's locality assumption that a sequence x_i can not depend on the value of j, i.e., whether M_1^B or M_2^B is measured. Strictly speaking, this locality condition cannot be submitted to actual test because it would require the production of two identical x_i sequences in two different experiments. Yet, in a way to be discussed later (with respect to the notion of macrolocality), it may be given an operational meaning by allowing that the identity of the sequences is attained after a suitable permutation of the elements of one of them. It should be realized, however, that, although the sequence x_i does not depend on which measurement is performed in region R_B, x_i is not independent of the specific measurement sequence y_1 or y_2 obtained in R_B (unless we have prepared the object system in such a way that its parts in spacetime regions R_A and R_B are statistically independent). We express this dependency as $x_i = x_i(y_1)$ and $x_i = x_i(y_2)$, respectively. Although the relation $x_i(y_j)$ between sequences x_i and y_j is not one to one (unless in very special cases in which x_i and y_j are perfectly correlated), it is nevertheless very much constrained because it *should* reflect the statistical correlation between x_i and y_j that is imposed on the EPR particle pair by the preparation process. For this reason, if sequence y_1' is a permutation of y_1, $y_1'=Py_1$, then the class of sequences x_i' for which $x_i'(y_1')$ and $x_i(y_1)$ yield the same correlation, is severely restricted (*one* sequence satisfying the requirement is the sequence $x_i' = Px_i$ which is permuted in the same sense as y_1). Hence, the possibility to form a quartet of measurement sequences is largely restricted by the preparation procedure.

It is important to compare Stapp's notion of locality with the notion of macrolocality as defined in Ref. 9, the latter referring to the macroscopic (statistical) measurement results only, and being satisfied by quantum mechanics[11]. In order that macrolocality be satisfied, it is necessary and sufficient that, for a given preparation procedure, if x_1 is a possible sequence, then any permutation Px_1 of x_1 is a possible sequence too, independently of the choice of M_j^B. Actually, a repetition of the experiment, either with the same M_j^B or with a different one, will in general not yield the same ordered sequence x_1 but one of its permutations Px_1, not to be identified with x_1 itself. It seems possible, however, to undo this permutation by applying the inverse permutation of P to Px_1, yielding x_1, thus making it possible to consider the same ordered sequence x_1 in two different experiments, as required by Stapp's definition of locality.

(We shall not be bothered by the fact that, in general, a permutation, transforming one sequence into another one, is not unique. For our purpose it is sufficient that at least one permutation exists.)

In order not to disturb the experimentally observed correlation between M_1^A and M_j^B, this same inverse permutation should be applied to the y_j sequence measured jointly with Px_1. (Also here a certain latitude in the choice of the permutation is ignored. Actually, the inverse of P is a member of a whole class of permutations that do not alter the correlation.)

We now come to the problem of how it is possible that Stapp reaches the conclusion that quantum mechanics is incompatible with locality, even though a seemingly equivalent notion of locality, viz., macrolocality, is satisfied by quantum mechanics. It is our opinion that, contrary to appearances, Stapp's notion of locality must be a stronger one than macrolocality. This, indeed, must be the case, because it does not seem to be possible to derive the existence of a quartet (x_1, x_2, y_1, y_2) from macrolocality. In order to see this, we consider the matching $x_1 = x_1(y_1) = x_1(y_2)$, in which two x_1 sequences, obtained in two different experiments, are identified by means of a permutation of one of the sequences (with simultaneous permutation of the corresponding y_j sequence), and an analogous matching $x_2 = x_2(y_1') = x_2(y_2')$ for the other two EPR measurements. In general y_i' will be different from y_i for $i = 1, 2$.

It is clear that a quartet exists if and only if it is possible to find permutations of the sequences such that $y_1 = y_1'$ and $y_2 = y_2'$. In this case it would be possible to satisfy Stapp's locality condition, which, for the sequence pairs under discussion, amounts to the equalities $x_i = x_i(y_1) = x_i(y_2)$, $i = 1, 2$. Macrolocality, however, does not imply the equality $y_i = y_i', i = 1, 2$. It only implies that $y_1' = Py_1$ and $y_2' = Qy_2$, in which P and Q may be *different* permutations. Stapp's locality condition requires the *possibility* that P and Q be equal.

It is questionable whether this extra requirement really is a necessary constituent of any notion of locality. As a matter of fact, the dependencies $x_i(y_j)$ are determined, in the first place, by the preparation procedure of the EPR particle pair, from which the correlations between EPR measurement outcomes follow. Stapp's requirement regarding the permutations P and Q can, for this reason, be interpreted as a requirement to be satisfied by the preparation procedure. Such a requirement, however, (1) seems unrelated to the locality question, (2) is not required by the QM formalism, and (3) is at variance with experiment, the latter conclusion following from the fact that the existence of a quartet implies satisfaction of the BI: Evidently, if the BI are not satisfied the permutations P and Q *should* be different, because in forming a quartet from the experimental outcome sequences it is inevitable to *change* the EPR correlations.

The lack of necessity for EPR measurement sequences to form quartets can be understood quite easily on the basis of a nonreproducibility hypothesis (NRH), conjectured by one of the authors[10] in the context of hidden-variables theories. This concept is applicable also in the present context, in which no hidden variables are considered. We may consider, as is done by Stapp[1], the measuring process as a random process, characterised by a random variable λ which is not a hidden variable, but which describes the fluctuations of *macroscopic* parameters by which the experimenter determines the mechanisms of preparation and measurement. We shall assume that each sequence of measurements corresponds with a sequence $\lambda = (\lambda_1, \ldots, \lambda_n)$ of values of the random variable. Combination of measurement results, obtained in different experiments, would have a meaning only if the λ sequences would be the same in the different experiments. This, essentially, is done by Stapp in order to obtain his quartet of measurement sequences. But, according to NRH, it is not to be expected that this can be realized in practice. Actually, if the random variable λ has a continuous domain, any finite sequence of values has a zero Lebesgue measure, and, hence, has a vanishing probability to be repeated in an actual experiment. Hence, a derivation of the BI along this line would at most yield that the BI are satisfied with vanishing probability.

However, even if *reproducibility* of the random variable is supposed, this does not imply the possibility of deriving the BI. Indeed, let us assume that the random variable λ can be prepared in a completely reproducible way. We might even suppose that the random variable has the same value in every individual realisation of the experiment. Now, the presupposition of *non*–CFD implies that the random variable does not determine the measurement outcome of each possible experiment in a unique way. For, if it did, a value could be attributed, in this way, to both the performed and the unperformed measurements, thus implying CFD, as would be the case if the *random* variable were interpreted as a *hidden* variable in a deterministic hidden–variables theory. In an instrumentalist setting, with this well–determinedness of the random variable, the preparation of a quantum mechanical *pure* state might be presumed to correspond. Then, the reproducibility assumption merely amounts to the possibility of preparing the same quantum mechanical pure state in different experiments. Hence, the random variable λ does not seem to play an essential role in a quantum mechanical investigation, and for this reason was left out of consideration in the foregoing. By doing so, we tried to avoid as much as possible the realist way of talking that is introduced by the reference to the random variable and which often obscures Stapp's treatment of the problem.

6. CONCLUSIONS

It follows from the foregoing analysis that the BI are not a necessary consequence of locality alone. As is well known, quantum mechanics is fully compatible with locality on the statistical level of measurement results[9,11] (called macrolocality by us). Macrolocality is the only kind of locality that is experimentally verifiable. Of course, the *possibility* that the four sequences x_1, x_2, y_1 and y_2 form a quartet is not in jeopardy. The preparation *might* be such that the quartet can be formed and, hence, the BI satisfied. Indeed, in many practical situations the BI are actually satisfied. Thus, in classical mechanics, being a theory in which CFD is valid, the BI are generally satisfied. But also in quantum mechanics many preparation procedures exist for which the BI are not violated.

It seems to us that, by introducing the quartet (x_1, x_2, y_1, y_2) CFD is essentially introduced again, a value being simultaneously attributed to each of the four (incompatible) observables. Such a simultaneous attribution only makes sense if the four values can be attributed to the *same* individual preparation. Hence, if it is impossible to measure the four observables simultaneously, it will be necessary to repeat the same individual preparation in order to obtain all values necessary for a derivation of the BI from the existence of quartets of individual measurement results. Without the reproducibility hypothesis (RH) there are no quartets, and hence there is no BI in the way derived by Stapp.

Moreover, notwithstanding the care taken by Stapp to avoid the assumption of CFD in his derivation of the BI, by neglecting the problems induced by RH and the objectivity assumption, Stapp essentially introduces CFD again. This is apparent from Ref. 1, p. 442, where it is stated that "Equations ... define, for each fixed λ, a quartet of values $(r_1(x_1,\lambda), r_2(x_2,\lambda))$. This quartet is defined by letting x_1 and x_2 vary over their two–valued domains. Each such quartet is a local quartet: within the quartet the value of r_j is independent of x_k, for $k \neq j$." The significance of this statement depends on the point of view from which it is considered. If the λ corresponds to *only one* (sequence of) measurement(s), then it is again CFD which leads to the conclusion of the existence of a quartet. If, on the contrary, it is assumed that each of the four couples $(r_1(x_1,\lambda), r_2(x_2,\lambda))$ corresponds to a different experiment, then the appearance of one single λ points to its *reproducibility* in different experiments. It follows that, if Stapp rejects the use of CFD, he needs an alternative reproducibility hypothesis (of those elements which nature uses to select an actual result) in order to be allowed to conclude to the existence of a quartet.

As discussed in Sec. 3 the assumption of reproducibility is considered as unproblematic in classical mechanics because there the objectivity assumption does not yield any problem. Neither does CFD, which can be seen as a direct consequence of this assumption. In quantum mechanics, however, the situation may be quite different in this respect.

As we demonstrated above, it is also not true that CFD or RH are a consequence of locality, and, hence, could be avoided by avoiding locality. The requirement of the existence of a quartet, and hence the introduction of CFD or RH, is performed as an extra requirement over the locality assumption. It seems to us that the only thing we can learn from a violation of the BI is that the *preparation* of the object system is such that no quartets can be formed from the actual measurement sequences, and from our analysis it hence follows that quantum mechanics is incompatible with CFD and RH.

That locality *allows* the formation of quartets and, hence, the derivation of the BI does not change this conclusion: Not everything that is allowed is realized in nature under all circumstances. Some preparations might conform to other, equally allowed, rules.

REFERENCES

1. H. P. Stapp, *Found. Phys.* **18**, 427, 833 (1988).
2. H. P. Stapp, in *Philosophical Implications of Quantum Theory*, J. Cushing and E. McMullin, eds. (Notre Dame University Press, Notre Dame, 1989); also, Lawrence Berkeley Laboratory Report LBL-24257, 1988.
3. H. P. Stapp, *Phys. Rev. D***3**, 1303 (1971); *Nuovo Cimento* **29B**, 270 (1975); **40B**, 191 (1977); *Found. Phys.* **10**, 767 (1980).
4. L. E. Ballentine, *Am. J. Phys.* **54**, 883 (1986).
5. N. Bohr, "The causality problem in atomic physics," in *New Theories in Physics* (International Institute of Intellectual Co-operation, Paris, 1939), p. 11–45.
6. J. F. Clauser and M. A. Horne, *Phys. Rev. D***10**, 526 (1974).
7. W. M. de Muynck and J. T. van Stekelenborg, *Ann. Phys. (Ser.7)* **45**, 222 (1988).
8. H. P. Stapp, private communication.
9. W. M. de Muynck, *Found. Phys.* **14**, 111, 199 (1984).
10. W. De Baere, *Lett. Nuovo Cimento* **39**, 234 (1984); **40**, 488 (1984); *Adv. Electronics and Electron Phys.* **68**, 245 (1986).
11. G. C. Ghirardi and T. Weber, *Lett. Nuovo Cimento* **26**, 599 (1979), *Nuovo Cimento* **78B**, 9 (1983); G. C. Ghirardi, A. Rimini, and T. Weber, *Lett. Nuov Cimento* **27**, 293 (1980).

NOTE

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