

Against Quantum Nonlocality

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Z. Naturforsch. **56 a**, 186–190 (2001); received February 11, 2001

Presented at the 3rd Workshop on Mysteries, Puzzles and Paradoxes in Quantum Mechanics, Gargnano, Italy, September 17 - 23, 2000.

It is shown that all quantum “contradictions” disappear if one drops the assumption of unique initial conditions for a hidden variable theory for individual quantum processes. Our proposal corresponds with a deterministic world evolution such that local physical conditions are nonreproducible, in agreement with empirical observation.

Key words: Quantum Nonlocality; Hidden Variable Theory.

The issue of this paper is the “mystery” of quantum nonlocality and contextuality originating from attempts to reconstruct the quantum formalism in terms of a purely classical model for individual quantum processes based, among others, on the validity of locality (LOC) and on what is commonly called counterfactual definiteness (CFD). All these attempts give rise to results which contradict quantum mechanics (QM) and are usually interpreted as evidence for non-local, contextual and acausal behaviour of quantum phenomena [1 - 3]. In particular, quantum nonlocality is the claim that in an entangled situation a measurement outcome not only depends on processes within its backward lightcone but also on other far-away entangled measurements.

Here we argue once more that, contrary to common opinion, nothing is wrong with the universal validity of locality and causality in quantum physics [4, 5]. This view is supported by the following considerations:

1. A violation of the locality principle has never been observed empirically.

2. Locality and causality are built in in all successful physical theories, such as the quantum theories for the fundamental interactions (quantum field theory, quantum chromodynamics, . . .); in these theories the basic commutation relation

$$[\hat{A}(x), \hat{B}(y)] = i\Delta(x-y) = 0 \text{ for } (x-y)^2 < 0 \quad (1)$$

for field operators $\hat{A}(x)$, $\hat{B}(x)$ expresses the belief in the universal validity of locality and causality.

3. The (deterministic) predictions of QM (which in general are for expectation values) are independent of far-away actions [6].

4. The program which tries to reconstruct QM from a more detailed theory of the classical type and which leads to a Bell inequality (BI) is ill defined because QM has been set up precisely to remedy the failure of classical theory. To see immediately that basic QM is violated by this program [5, 7] one may start from the identity [8]

$$(\hat{A}\hat{B} + \hat{A}'\hat{B} + \hat{A}\hat{B}' - \hat{A}'\hat{B}')^2 = 4\mathbb{I} - [\hat{A}, \hat{A}'][\hat{B}, \hat{B}'], \quad (2)$$

where the observables \hat{A} , \hat{A}' , \hat{B} , \hat{B}' represent correlated (entangled) measurements along 4 possible experimental settings: \vec{a}, \vec{a}' in one region L by an observer O_L and \vec{b}, \vec{b}' in another spacelike separated region R by an observer O_R . From (2) it follows [8] that the expectation value of the left hand side satisfies Cirel'son's inequality [9]

$$|\langle \hat{A}\hat{B} \rangle + \langle \hat{A}'\hat{B} \rangle + \langle \hat{A}\hat{B}' \rangle - \langle \hat{A}'\hat{B}' \rangle| \leq 2\sqrt{2}. \quad (3)$$

By substituting zero for the commutators in the rhs. of (3) one gets a BI with 2 replacing $2\sqrt{2}$ in (3) [10]. This shows that the violation of BI, viz. having the RHS of (3) exceeding 2, is predicated upon $[\hat{A}, \hat{A}']$ and

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$[\hat{B}, \hat{B}']$ being nonzero, i. e. the nonvanishing of *local, single* particle's, commutators. Also the numerical value of the violation is given by the numerical value of these commutators. From this derivation of a BI it may be concluded that it is the noncommutativity of quantum observables pertaining to a *single* quantum system, instead of locality, that plays the crucial role in the violation of the BI by QM.

5. Sticking to quantum nonlocality would complicate the underlying physics because in one and the same quantum process one should have at the same time a causal and a noncausal influencing. The noncausal influencing, preserving LOC, is between the preparation and observation by e. g. O_L , (the *possible* outcomes by O_L , O_R are determined by the preparation, but the *single actual* outcomes are determined by *chance*, at least in the Copenhagen interpretation of QM (CIQM)); the causal influencing, violating LOC, should occur between observation by O_L and observation by O_R : for observation by O_L , O_R along the same direction it is the outcome by O_L which determines causally (but instantaneously, i. e. violating LOC) the outcome by O_R .

Hence, all empirical and theoretical evidence is against the idea of giving up locality and causality in quantum phenomena. Of course, this does not yet explain in a more detailed way the origin of the contradictory results arrived at by classical reasoning. We will now give a simple and convincing reason for that. To proceed we summarize first our starting points.

6. We adhere to a pragmatic interpretation of physical theory in general and of quantum mechanics in particular. According to this interpretation, physical theories predict *in a deterministic way* the outcomes of future measurement events given the outcomes of past or present ones [11]. This interpretation is a very reasonable one in that it corresponds very well with the actions of physicists in real laboratory experiments. Anything else that is added gives rise to other interpretations but these additions may be considered as superfluous as they do not alter predictions for outcomes of observations. The consistency of this point of view is so well founded that one may even claim that QM does not need an interpretation [12]. This standpoint is suggested also by Van Kampen's theorem IV [13] according to which "... whoever endows ψ with more meaning than is needed for computing observable phenomena is responsible for the consequences". This is often overlooked, and because it stresses the basic and essential importance of the

availability of a mathematical, i. e. deterministic, algorithm, it may be used as a reliable guide in foundational studies. Otherwise stated, any physical theory concerns results of empirical observation and the basic principles of the theory should at least agree with the empirical data, such as locality.

7. In agreement with 6. above we thus require that physical considerations always are accompanied by a formal deterministic scheme, and that due attention should be given to the importance of the initial conditions. This point has already been discussed long ago by Houtappel, Van Dam, and Wigner [14] who stressed explicitly that the initial conditions and the laws of physics play an equally important role "... because the laws of nature do not lead to observable consequences unless the initial conditions are given ...". In fact, in a pragmatic interpretation these initial conditions concern the theory's state which, in terms of EPR's terminology, may be considered as representing some "element of physical reality". Applied to the above mentioned program this entails the assumption of the availability of a deterministic formal scheme for *individual* quantum processes. This immediately implies the introduction of supplementary, hidden, variables λ , not contained in the quantum formalism.

8. Determinism is a formal property of any theory. Because the quantummechanical statistics is the result of the accumulation of individual events, we opt for the following reasonable approach (among other reasonable ones): because the statistics obey definite, deterministic, laws it seems plausible that also the individual quantum processes obey definite, deterministic, laws; (how could one understand otherwise e. g. the lawfull behaviour of the statistics, the prediction with certainty of the outcome of a correlated measurement in the case of perfect correlation, etc.) Statements in favour of such an approach have been made frequently in the course of the development of QM (and extensions). Jammer [15] remarks: "It has been claimed that even the most 'progressive' theoretician believes at the bottom of his heart in a strictly deterministic, objective world even if his teachings categorically deny such a view ... It explains, however, why some physicists rejected the prevailing probabilistic interpretation of quantum mechanics and tried to demonstrate that the existing theory in spite of its spectacular success is only a provisional approximation to a deeper scientific truth." Another statement by Stapp [16] supports this view: "Some writers claim to

be comfortable with the idea that there is in Nature, at its most basic level, an irreducible element of chance. I however, find unthinkable the idea that between two possibilities there can be a choice having no basis whatsoever. Chance is an idea useful for dealing with a world partly known to us. But it has no rational place among the ultimate constituents of Nature.” Recent proponents of determinism at all levels of description are e. g. ’t Hooft [17] and Weinberg [18].

We shall now describe our simple resolution of the so-called “incompatible quantum results”. In agreement with our starting points above we shall adhere to the view that for each observation there exists a causal reason on a deeper level of description, i. e. we will assume that, instead of chance, it is our *ignorance* of the precise individual state following a preparation or a measurement which is responsible for the uncertainty about future outcomes. Because the variables in QM allow only the deterministic prediction of the statistics we will need supplementary (“hidden”) variables and a new (“hidden variable”) theory (HVT) allowing the prediction of individual outcomes for specific initial conditions. Here we remark already that it is Nature itself that determines which initial conditions are realizable and whether they are reproducible or not in subsequent runs of an experiment (in the same way that Nature does not allow the occurrence of negative mass in Newton’s theory according to which particles should move upwards in a gravitational field instead of falling down). Such a HVT for individual quantum processes should conform the general requirements of a theory, namely its principles should agree with empirical data (such as locality) and the initial conditions should allow to predict in a causal and deterministic way the unique outcome of future events.

9. Consider then two identically prepared ensembles consisting each of N individual preparations. Each preparation corresponds with the same pointer position(s) so that the two ensembles may be characterised quantummechanically by two state vectors $|\psi\rangle$ and $|\psi'\rangle$. Because identity is to be understood here also in a quantummechanical sense, we will have that $|\psi'\rangle \equiv |\psi\rangle$. With the purpose to compare the two ensembles element by element we will distinguish the two ensembles by labels (a) and (b), we label each element in an ensemble by i , and let depend the HV λ on space-time coordinates x^μ . In this way we may write the following for our two ensembles:

$$\{\lambda(x_{i;(a)}^\mu), i = 1, \dots, N\} \sim |\psi\rangle, \quad (4)$$

and

$$\{\lambda(x_{i;(b)}^\mu), i = 1, \dots, N\} \sim |\psi'\rangle. \quad (5)$$

We now remark that the identity with respect to the QM state vectors does not necessarily mean identity with respect to the HV states and, hence, does not imply

$$\lambda(x_{i;(b)}^\mu) = \lambda(x_{i;(a)}^\mu), i = 1, \dots, N, \quad (6)$$

i. e. the sets of individual states

$$\{\lambda(x_{i;(a)}^\mu), i = 1, \dots, N\}, \{\lambda(x_{i;(b)}^\mu), i = 1, \dots, N\} \quad (7)$$

are not necessarily identical, even after any possible reorganization of the elements of the sets. In the domain of application of classical mechanics (CM) and of QM Nature allows the preparation of physical situations such that their mathematical representation is by identical functions, i. e. the corresponding physical states are reproducible. However, it is not evident that Nature allows the same to be true for *individual* HV or subquantum states, i. e. this remains a supplementary assumption which may be invalid at a subquantum level of description. Now it is seen that the validity of this hypothesis has tacitly been assumed in all existing argumentations leading to incompatible results of QM [5]. In previous work [4, 19] we called this the “nonreproducibility hypothesis (NRH)”. As is the case with LOC, this hypothesis is in full agreement with the empirical fact that past, present and future are observably distinct. Hence, “nonreproducibility of individual HV or subquantum states” may be an elegant solution for removing all quantum paradoxes.

Our conclusions are as follows.

10. A consistent local hidden-variable interpretation of QM may be set up with the following main characteristics: physical reality may be represented by a subquantum state $\lambda(x^\mu)$ which evolves in a way such that:

- (formal) determinism and causality are valid, just like in CM and in QM. In the case of *correlated* observations the notions *cause* and *effect* apply between the preparation and the correlated measurements, but *not* between the correlated measurements (which may be *simultaneous*) themselves; there is a correlation because there is a common past;

- LOC remains valid at the level of individual quantum processes;

- individual physical situations represented by $\lambda(x^\mu)$ are nonreproducible, i. e. cannot be “copied”. As a consequence, the BIs and similar contradictory results (e. g. of the Kochen-Specker type) are not derivable for such ensembles.

11. It is immediately seen that the usual application of CFD (which presupposes the reproducibility of initial conditions) breaks down in our approach because of the property NRH. This means that in the domain of application and validity of the present QM physicists are not allowed to reason what would have happened if instead of the actual choice another choice had been made, or: the initial conditions cannot be kept constant, in agreement with empirical observation.

12. Our NRH is compatible with the empirical existence of an arrow of time and agrees e. g. with statements such as one of Aharonov, Bergmann, and Lebowitz (ABL) [20]: “One of the perennially challenging problems of theoretical physics is that of the ‘arrow of time.’ Everyday experience teaches us that the future is qualitatively different from the past, that our practical powers of prediction differ vastly from those of memory, and that complex physical systems tend to develop in the course of time in patterns distinct from those of their antecedents.”

13. In our approach we get a reconciliation between Einstein’s and Bohr’s views:

- EPR’s elements of physical reality correspond with initial conditions in a HVT but should be time-dependent, contrary to what EPR thought to be the case (while reasoning within the CIQM). Because the evolution of physical processes is according to deterministic laws, Einstein’s dictum that “God does not play dice” is met.

- If physics is defined as being concerned, as Bohr would have it, with observable, *reproducible*, phenomena then a HVT, which would describe the dynamics of $\lambda(x^\mu)$, would be, at least at present, of no practical use because of the principal failure to know exactly the initial conditions; in that case it will be difficult to surpass QM which then may be considered a complete “FAPP” theory because it answers all possible questions which may be posed by human observers. In this case it is not God who plays dice but the human observer because of his intrinsic and unsurpassable limitations.

We conclude that in our approach locality and causality still remain the fundamental cornerstone of our physical theories, including QM. Our approach does only affect possible HVTs and has no influence at all on the new domain of quantum information theory which uses the present, still successful, quantum formalism. Our proposal also gives a reasonable explanation for the noncommutativity of certain quantum observables. The validity of CFD on a subquantum level is restricted as compared to its use in CM and in QM in the sense that in counterfactual considerations identical initial conditions may no longer be assumed. At this level the use of density functions such as $\rho(\lambda)$ also becomes questionable because, although it may be assumed that $\rho(\lambda)$ is reproducible, this may no longer be the case for finite sets of HVs in different runs of an experiment, i. e. a supplementary time-label should be added to the elements composing these sets, suggesting that the sets are not identical, even after any possible reorganisation of the elements of the sets.

JDN acknowledges financial support from IWT (“Flemish Institute for the scientific-technological research in industry”)

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