On the Relation between the Einstein-Podolsky-Rosen Paradox and the Problem of Nonlocality in Quantum Mechanics

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The EPR problem is studied both from an instrumentalistic and from a realistic point of view. Bohr's reply to the EPR paper is analyzed and demonstrated to be not completely representative of Bohr's general views on the possibility of defining properties of a microscopic object. A more faithful Bohrian answer would not have led Einstein to the conclusion that Bohr's completeness claim of quantum mechanics implies nonlocality. The projection postulate, already denounced in 1936 by Margenau as the source of the EPR paradox, is found to be also at the origin of the nonlocality conundrum. Its unobservability in EPR-like experiments is demonstrated, thus showing the redundancy of the idea of nonlocality in the instrumentalist interpretation of quantum mechanics. It is argued that also from a realist point of view there is no reason to assume nonlocality. The relevance of Bohm's quantum potential and of Bell's inequalities with respect to the (non)locality problem is discussed.

1. THE DILEMMA: COMPLETENESS OR NONLOCALITY

The problem whether quantum mechanics is complete may be reformulated as the question whether the domain of application of this theory is universal. This problem seemed to have been settled, after a prolonged discussion between Einstein and Bohr, in favor of the completeness claim of the latter's Copenhagen interpretation. It has, however, obtained renewed attention ever since it was deemed possible to devise experiments (testing the so-called Bell inequalities) which might be expected to give results which are *not* described by quantum mechanics. Most of these experiments actually have turned out *not* to belong outside the domain of quantum mechanics. However, far from being conceived as a new victory of the completeness thesis, this result is nowadays often judged to pose a new problem because of the essential nonlocality of the microphysical world it seems to imply. It is the purpose

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of this paper to *question* whether the EPR problem and the Bell inequalities have any bearing on the problem of (non)locality in quantum mechanics, and whether the results of recent EPR-like experiments really should be interpreted as evidence of a fundamental nonlocality or inseparability of the microphysical world.

1.1. Observed and Unobserved Reality

The completeness problem of quantum mechanics, as conceived by me, is closely connected with the question of whether all measurements to be performed in the microphysical world can be described by quantum mechanics, that is, whether quantum mechanics gives a complete description of *observed* reality. In the famous article by Einstein, Podolsky, and Rosen(1) it was not *observed* reality, but *unobserved, objective* reality, that was intended to be demonstrated as not completely describable by quantum mechanics. It is understandable that this analysis hardly bas been a serious challenge to the Copenhagen completeness claim, since the absence of experimentally verifiable consequences makes the analysis itself rather incomplete. By omitting to exhibit a way of demonstrating a possible experimental insufficiency of quantum mechanics, the completeness problem as raised by EPR remained on a purely metaphysical level, and could be dealt with too easily by Bohr(2) by pointing at an ambiguity in EPR's conception of objective reality.

The difference between *objective* reality and *observed* reality seems to me to be of crucial importance for the interpretation of quantum mechanics. According to Bohr, knowledge about the microphysical world is knowledge about a microscopic object as it is situated in a well-defined measurement context. So, our knowledge does not regard an isolated object (objective reality) but an object that may be influenced by the interaction with the measurement arrangement. In microphysics this interaction can neither be neglected nor avoided. This makes the situation essentially different from what we are accustomed to in macroscopic observation. Whereas in macrophysics observed reality can be identified, to any desired accuracy, with an objective reality that can be viewed as independent of any measurement arrangement, this is impossible in microphysics. Much of the Einstein-Bohr debate, referred to above, has to do with the (im)possibility either to eliminate or to compensate for the interaction between microscopic object and measuring instrument. The ERP proposal can be seen as an ultimate attempt to devise a measurement procedure by means of which it is possible to obtain knowledge on a microsystem without in any way disturbing it by the measurement act. Although it pressed Bohr to extend his interactional interpretation of quantum mechanics to a more general relational conception,(3) it could not upset his conviction that Einstein's complete objective knowledge is unattainable, or at least unverifiable. With Bohr the quantum mechanical wave function does not describe an objective reality. Moreover, as we shall see in Section 2, by more closely sticking to his original ideas in analyzing the EPR problem, Bohr could easily have evaded a reproach of theory change,[4] and rigorously could have maintained his interactional interpretation. It should be acknowledged that Bohr, presumably, is right in supposing that no objective knowledge is possible which is independent of the way it is obtained and which is also liable to experimental verification. Even if the knowledge is obtained without a direct interaction with a measuring instrument (as is the case in the EPR problem) its verification yet demands such an interaction.

Einstein doubtless was aware of this, even though in the EPR problem the emphasis is on the description of *objective* reality. Not the mere fact that observation disturbs the object, but the precise way in which this disturbance takes place, is the real content of the Bohr-Einstein controversy. By Bohr's completeness claim this disturbance is standardized in such a way that any measurement automatically satisfies quantum mechanics. It was the alleged unanalyzability of Bohr's "quantum phenomenon,"[5] governing the interaction between object and measuring instrument, which induced Einstein to characterize Bohr's views as a "tranquilizing philosophy." Admittedly, the domain of quantum mechanics has a considerable extension, and it has proved to be extremely difficult to invent measurement procedures that cannot be coped with by quantum mechanics. However, it is not unreasonable to surmise that the typical characteristics of a quantum mechanical measurement have no more universal validity than had the macroscopic measurements of classical mechanics. The possibility of measurement processes, not satisfying precisely the characteristics of the measurement interaction as prescribed by quantum mechanics, cannot be excluded. Unless we want to maintain quantum mechanics as universally valid by way of convention, it seems expedient to analyze the microscopic measurement process in all its details in order to obtain an idea in which way the domain of quantum mechanics can be transcended.

Contrary to Bohr's understanding of the meaning of the quantum mechanical formalism, in present-day formulations and interpretations a tendency can be observed toward the conception of the quantum mechanical wave function as the description of an *isolated* system, that is of an *objective* reality. In most textbooks of quantum mechanics the ideas of Bohr are referred to only in an introductory chapter without much impact on the bulk of the presented theory. Following von Neumann the quantum mechanical measurement is treated in an axiomatic way, the axioms actually specifying what a quantum mechanical measurement is. The measurement apparatus and the interaction between object and measuring instrument, however, remain completely out of sight, thus suggesting that the measurement results can be attributed to the object system as objective properties. It is remarkable to observe that the axiomatic treatment of quantum mechanics, which is possible only by virtue of Bohr's completeness claim, at the same time tends to obscure that other principal theme of Bohr's, viz. the impossibility of knowledge which is independent of the measurement arrangement.

1.2. Instrumentalism, Realism, and Nonlocality

The idea that quantum mechanics provides a *complete* description of an *objective* reality has triggered a line of thought which plays an important role in contemporary discussion on the interpretation of quantum mechanics. It was once again Einstein[6] who concluded that from Bohr's completeness claim of quantum mechanics it follows through the EPR reasoning that quantum mechanics is incompatible with the principle of locality and should imply action at a distance. Since Einstein was not aware of any physical phenomenon making it probable that the principle of locality should be given up, he concluded that the description of quantum mechanics should be considered as incomplete.

In the following it will be demonstrated that Einstein's reasoning is not compulsory because it is based on an interpretation of the wave function as a description of an *objective* reality. If we rigorously stick to Bohr's idea of the wave function as a description of an *observed* reality in interaction with a well-defined measurement arrangement, then it would even be possible to maintain Bohr's completeness claim without being committed to nonlocality. As we shall see in Section 2, with respect to this issue Bohr's reply[2] to EPR has caused quite a bit of confusion, partly because it was not easy to understand, partly because the answer seems to be less Bohrian than it could have been.

Of course, this does not imply either that quantum mechanics *is* complete or that the reality described by quantum mechanics *is* local. It just highlights the role that is played by explicit or implicit assumptions which are made in accepting a certain interpretation of the formalism. As is well known, it is possible to circumvent the problem of (non)locality complete by narrowing down the interpretation of quantum mechanics to a purely instrumentalistic one. Then, the postulate of local commutativity guarantees that measurements performed in causally disjoint regions of space-time do not influence each other.[7] Note that in this interpretation the EPR problem does not have any meaning because that problem does not refer to the outcomes of measurements which are actually performed, but to an unobserved reality.

An instrumentalistic interpretation of the quantum mechanical wave function need not be at variance with the idea of an underlying reality. It is argued in Section 3 that the projection postulate was introduced in quantum mechanics precisely because of the feeling that the wave function should describe the object itself rather than the phenomena induced by the latter in measuring instruments. As early as 1936 Margenau[8] pointed out that it is the projection postulate which is causing the conceptual difficulties that are brought forward by the EPR proposal. It is, indeed, clear that by means of the projection postulate it is possible to incorporate EPR's element of physical reality in the quantum mechanical formalism. So, the projection postulate essentially is also at the basis of Einstein's non-locality verdict. In Section 3 the unobservability of a projection as prescribed by the projection postulate is demonstrated. So, from an instrumentalistic point of view there is no reason to maintain this postulate as an axiom of quantum mechanics. Within the domain of quantum mechanics, then, in compliance with the principle of local commutativity, also the nonlocality which is implied by the projection postulate can be ignored as being unobservable.

This leaves open the possibility that locality could be violated outside the domain of quantum mechanics. This problem is discussed in Section 4. It is argued there that, contrary to a widespread belief, violation of the Bell inequalities by the results of EPR-like experiments does not imply non-locality of realistic theories reproducing the results of quantum mechanics. By the Bell inequalities not only local, but also nonlocal, realistic theories are seen to be incompatible with quantum mechanics if they satisfy the axioms of Kolmogorovian probability theory. From this result it is seen that Bell's locality assumption is redundant in deriving the Bell inequalities.

2. BOHR AND THE EPR PAPER

2.1 Some Elements of Bohr's Philosophy

The challenge of the EPR[(1)] experiment is to be considered as an ultimate attack on the alleged completeness of quantum mechanics. By closely sticking to the idea of a "quantum phenomenon"[(5)] Bohr had been able to defend his completeness thesis successfully against previous attempts on Einstein's part to find the flaw in quantum mechanics. Indeed, in discussing Heisenberg's uncertainty or indeterminacy principle, Bohr had always been able to demonstrate the impossibility of obtaining more precise knowledge on both of two canonically conjugate variables, due to a disturbing influence on one variable by changing the measurement setup in a way which is necessary to obtain knowledge about the second variable. Bohr's quantum phenomenon represents the impossibility in the microscopic domain to neglect or to compensate for the interaction between the measuring instruments and the object under observation. The inseparability of object and measuring instrument is expressed by Bohr in a "quantum postulate,"formulated by Scheibe[(9)] as follows: "Every quantum phenomenon has a feature of wholeness or individuality which never occurs in classical physics and which is symbolized by the Planck quantum of action."

As is well known,[(10)] Bohr was not a realist in the sense that a disturbance of some variable by the interaction between object and measuring instrument could be interpreted as a disturbance of a value which was possessed by the object prior to the measurement. On the contrary, in Bohr's view the quantum postulate gives expression to the fact that it is meaningless to assume an object to have any value of any variable outside the context of the measurement situation serving to determine this value. Stated differently, the interaction between the object and the measuring instrument determines the possibility of *defining* the variable measured by this instrument. By Jammer[(3)] this view is called "the interactionality conception of microphysical attributes."Hence, outside the context of the measurement of some specific variable, according to this view this variable is not even defined.

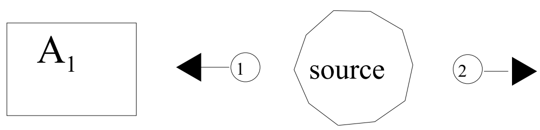
2.2. The EPR Reasoning

It seems to me that the EPR setup (see Fig. 1) was contrived precisely to evade the interaction with the measuring instrument. By considering a pair of correlated particles, 1 and 2, which are far apart, and, hence, allegedly no longer interacting, it seems possible to obtain information on particle 2 by performing a measurement on particle 1 only, "without in any way disturbing"particle 2. So, the ëlement of physical reality,ïntroduced by EPR, in the first place has the meaning of a property which is possessed by the object in an objective way, i.e., without interfering with any measuring instrument. It is this element of physical reality which brings EPR to their verdict of incompleteness of quantum mechanics.

In order to be able to perform a sound evaluation of the arguments which are used, I first will give a concise review of the EPR reasoning. This reasoning is based on the possibility that the wave function of the combined system of particles 1 and 2 can be expanded in two different ways so as to exhibit on the one hand a correlation between two observables A_1 and A_2 of particles 1 and 2, respectively ($[A_1, A_2]_- = 0$), and on the other hand a correlation between observables B_1 and B_2, such that $[B_1, A_1]_- \neq 0, [B_2, A_2]_- \neq 0, [B_1, B_2] = 0$. Thus, if $\phi_j(x_i)$ ($\psi_j(x_i)$) are eigenfunctions of A_i (B_i), we have

$$\psi(x_1, x_2) = \Sigma_j c_j \phi_j(x_1)\phi_j(x_2) = \Sigma_j d_j \psi_j(x_1)\psi_j(x_2) \tag{1}$$

In this state a measurement of A_1 (B_1) yields the value a_j (b_j) with probability $|c_j|^2$ ($|d_j|^2$), whereas a simultaneous measurement of A_1 and A_2 (B_1 and B_2) will always yield the same value for the observables of particles 1 and 2. According to EPR this means that we can measure A_2 and B_2 by measuring A_1 or B_1, respectively. Incompleteness of quantum mechanics follows, on their view, because in this way it



Figuur 1: Experimental arrangement according to the EPR proposal.

is possible to attribute to particle 2 two elements of physical reality, corresponding to the incompatible observables A_2 and B_2, which elements cannot be described by quantum mechanics.

2.3. Bohr's Answer to EPR

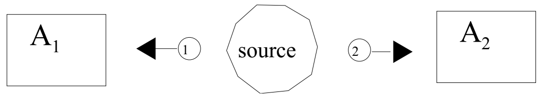
As to Bohr's reply(2) to the EPR challenge we cannot but join Popper's(4) remarks that Bohr's counter-argument is very hard to understand, and that no presentation of it can be asserted to represent exactly what Bohr wanted to say. For this reason the following presentation of Bohr's answer possibly does not completely match Bohr's ideas. Since, however, there is considerable similarity with the presentations given by Popper(4) and Jammer(11) (although I will try to lay the emphasis somewhat differently), there is some ground not to be too pessimistic.

Stated in a concise way, Bohr's answer to EPR amounts to the following. If A_1 is measured, then A_2 is determined by the correlation between A_1 and A_2. If B_1 is measured, then B_2 is determined by the correlation between B_1 and B_2. Since A_1 and B_1 are incompatible, they cannot be measured simultaneously. Hence, if A_1 is measured, B_1 is not defined, and neither is B_2. Consequently, A_2 and B_2 are not simultaneously defined, and the EPR incompleteness conclusion is not justified.

2.4. Analyses of Bohr's Answer to EPR

Bohr's answer(2) to the challenge by Einstein, Podolsky, and Rosen(1) has given rise to a wealth of reactions in the physical and the philosophical literature which cannot be dealt with here in its full completeness. I shall be content to restrict myself to those reactions which are relevant to the problem discussed in this article. Thus, I shall leave completely out of consideration those reactions(12) dealing with the issue of a possible subjectivistic interpretation of the formalism of quantum mechanics. By consistently deploying a frequency interpretation of probability, it seems very well possible to deny the observer any active role exceeding registration of the pointer positions of a macroscopic measuring instrument or occasional selection of subensembles from the ensemble of these events, the latter being described by a state vector or a density operator.

2.4.1. From an Interactional to a Relational Interpretation. Popper(4) as well as Jammer(11) interpret Bohr's answer as a *change* of interpretation, because now what is defined of particle 2 is determined by a measurement on particle 1 with a measuring instrument that does *not* interact with particle 2. Hence, the measuring instrument no longer exercises its definitory function by means of a direct interaction. It suffices that there is a *relation* between the measuring instrument and particle 2,



Figuur 2: Experimental arrangement for a direct correlation measurement.

which is constituted by a combination of, on the one hand, the interaction between measuring instrument and particle 1 and, on the other hand, the correlation between particles 1 and 2. Thus,

$$\text{relation} = \text{interaction} + \text{correlation} \tag{2}$$

Popper[(4)] compares this relation with a coordinate system. Depending on the choice of the measurement arrangement for the measurement on particle 1 (either A_1 or B_1) a different coordinate system is set up, with respect to which the second particle can be described. The two coordinate systems corresponding to the measurements of A_1 and B_1 cannot be combined into one if A_1 and B_1 are incompatible or complementary. By the correlations this incompatibility or complementarity is transferred to the observables A_2 and B_2. In Bohr's own words,[(2)] there is "no question of a mechanical disturbanceöf particle 2 by the measurement on particle 1, but "there is essentially the question of an influence on the very conditions which define the possible types of predictions regarding the future behavior of the system."Indeed, this can be interpreted as a change of the theory in which the observables of a system need no longer be defined by a direct physical interaction with the measuring equipment, but can already be defined through existing correlations with systems it interacted with in the past, and measurements performed on those systems.

2.4.2. Comment on the Question of Theory Change. Before discussing other reactions on Bohr's reply, I first want to make some comments myself, because it seems to me that Bohr could have prevented Popper's reproach of theory change by sticking more faithfully to his original ideas. Indeed, Bohr's answer is less Bohrian than it could have been. If Bohr had considered the correlation of the two particles as an ordinary variable, he should have replied that *this correlation is only defined within the context of a correlation measurement*, because only in this way is a variable defined. Since the $A_1 - A_2$ correlation cannot be measured simultaneously with the $B_1 - B_2$ correlation, these correlations are not defined simultaneously, and the whole EPR objection evaporates because this is based on the *simultaneous definition of both correlations.* Moreover, a correlation measurement requires a measurement on both particles (see Fig. 2). Hence, the interactionality conception of microphysical attributes can be maintained in its full rigor. No theory change is necessary!

It is not clear why Bohr did not run counter to EPR's contention that both correlations are defined irrespective of their being measured. On the contrary, Bohr accepts(2) that "In this arrangement (i.e., only one particle being measured on)[2], it is therefore clear that a subsequent (i.e., after the preparation of the correlated system)[2] single measurement either of the position or of the momentum of *one of*[3] the particles will automatically determine the position or momentum, respectively, of the other particle with any desired accuracy,..."Perhaps, Bohr had in mind that a determination of this kind is gratuitous unless it is checked by some measurement performed on the second particle. Indeed, Bohr,(2) in this respect, refers explicitly to the "possible types of *predictions*[3] regarding the future behavior of the system."If by "predictionsïs meant here the prediction of the measurement results of a measurement of the correlation variable *which is actually performed*, then the conditions for a definition of the correlation are satisfied, and Bohr's answer could be interpreted in the strictly Bohrian way.

As we shall see in Section 2.4.3, this interpretation of Bohr's answer would be in line with an instrumentalist interpretation of the quantum mechanical formalism, thus endorsing an instrumentalist understanding of Bohr's philosophy. If this were true, however, it is not clear why Bohr did not emphasize the necessity that a measurement on both particles should be actually performed lest a correlation between the particles be well defined. It seems to me that Bohr in his reply to EPR is rather compliant with the Einsteinian idea that the correlations between the particles are objectively real and are defined independently of whether a measurement is actually performed. Thus, with respect to a position measurement on particle 1 *only*, Bohr says(2): "By allowing an essentially uncontrollable momentum to pass from the first particle into the mentioned support, however, we have by this procedure cut ourselves off from any future possibility of applying the law of conservation of momentum... and therefore have lost our only basis for an unambiguous application of the idea of momentum in predictions regarding the behavior of the second particle."

This need not be interpreted -and it explicitly *should not* be- as signifying that in a position measurement a preexisting momentum correlation is disturbed by the uncontrollable momentum transfer. With Bohr this should be interpreted as a lack of definition of the momentum correlation in a position measurement because of a lack of definition of one of the momenta. Also, the above quotation need not be interpreted as signifying that, on measuring, e.g., momentum of the first particle, the momentum correlation of particles 1 and 2 is well defined. On the contrary, the quotation specifies a circumstance in which the correlation is *not* well defined, and it would be a logical error to conclude from this negative statement to the positive assertion of the existence of this correlation under different circumstances.

Yet, it seems to me that this existence is at least *suggested* by Bohr's paper, and, in any case, it is interpreted in this way by Einstein, as we shall see shortly. Bohr's

[2]My insertion.

[3]My italics.

reference to the (non)applicability of the law of momentum conservation provokes a picture in which momentum of the combined system of the two particles may be treated classically if the momentum is measured of one of the particles only. As we shall see in Section 2.5, there are some reasons to doubt whether Bohr's philosophy was purely instrumentalistic. His insistence on defining a variable in *classical* terms opens up the possibility of considering a variable as real whenever it is well defined. If this possibility is combined with a specification of the condition on which a variable is well defined, we end up with the possibility of a contextualistic realism, in which reality is determined by the complete measurement arrangement.

It is possible, though not necessary, to understand Bohr's answer to EPR by taking into account on Bohr's part an inclination toward a realism in the sense discussed here. At least, it would explain why Bohr did not deal with the EPR challenge on the basis of the instrumentalistic argument given above, but, for instance, referred to the realistic notion of "the behavior of the second particle." On the other hand, it does not explain why Bohr did not emphatically refute Einstein's suggestion that a correlation can be real if only one particle is measured. Possibly, he did not recognize the momentum and position correlations as ordinary variables, to be treated on an equal footing with momentum and position itself. Or, Bohr may have felt his position strong enough to concede to Einstein the existence of a correlation that is not actually measured because, even with this handicap, he thought to be able to win. However this may be, it is clear that Bohr did not choose the most straightforward way to defend his views against the EPR challenge. Even without giving up realism it would have been possible for him to maintain his position merely on the basis that (i) quantum mechanics does not describe an objective unobserved reality but an observed reality which is in interaction with measuring instruments, and (ii) variables are defined *only* in the context of a measurement arrangement serving to determine this variable.

2.4.3. Instrumentalist Reactions. Instrumentalism takes the formalism of quantum mechanics to be just an instrument to predict the outcome of a measurement performed in the atomic domain. So, quantum mechanics does not describe reality as such. It is just about the values and the relative frequencies of quantum mechanical observables. Hence, in the instrumentalist option the EPR objection is meaningless, because it is a statement about a system (particle 2) that is *not* observed.

Although Bohr seems not to have been an instrumentalist in the sense that he did not completely reject the notion of reality,[10] his requirement that variables or attributes are defined only if there is present a measurement arrangement for this variable is sufficiently similar to the instrumentalist position that Bohr could be hailed as a champion of positivistic instrumentalism. Possibly for this reason -and because of the relative popularity of positivism among physicists- the discussion between Bohr and Einstein did not raise much interest in the years following the publication of the two articles on the EPR "paradox": Bohr was generally considered as the winner in the debate. Already before Bohr's answer was published, Ruark[13] has pointed out that "the question (of incompleteness) cannot be decided by reasoning based on accepted physical principles. The arguments which can he advanced on either side seem to be far from conclusive, and the issue involved appears to be a matter of personal choice or of definition."The EPR ëlement of physical reality"being the main issue in this matter of personal choice, the positivist inclination to use Occam's razor has certainly been instrumental in gaining Bohr his victory.

It is interesting to note, however, that Ruark also deems arguments to be advanced from Bohr's side to be inconclusive. Thus, he points out that it is possible to consider a measurement of A_1 as a measurement of the correlated observable A_2 by way of definition. Thus, turning to advantage the existing correlation, the A_1 measurement could be interpreted as an *in*direct A_2 measurement. If no distinction is made between direct and indirect measurements, the A_2 variable may be supposed to be defined in the Bohrian sense by the arrangement measuring A_1. This does not seem to be very far from the answer Bohr actually has given (cf. Section 2.3). Ruark, however, evidently considers this definition of an A_2 measurement by measuring A_1 not less arbitrary than EPR's definition of the ëlement of physical reality."

2.4.4. Comment on the Question of Indirect Measurement. Nowadays, it seems to me the possibility of considering the A_1 measurement as a kind of indirect A_2 measurement has been rather widely accepted. This does not appear to be unreasonable, because, due to the correlation expressed by the wave function (1), any subsequent measurement of A_2 would *with certainty* yield the same value for A_2 as was obtained for A_1. It has even been proposed[14] to exploit the measurement setup as a simultaneous measurement of A_2 and B_2: since A_1 and B_2 are compatible, they can be measured simultaneously; by declaring the value of A_1 to be the measured value of A_2 we simultaneously obtain a value for A_2 and B_2.

In de Muynck, Janssen, and Santman[15] this proposition was criticized on the basis of its highly unusual consequences. It is now possible to prove[7] the impossibility of viewing the above-mentioned procedure as a simultaneous measurement of two incompatible observables A_2 and B_2. This proof is based on the assumption that the measurement process is an ordinary microscopic process to be described by quantum mechanics. More general it suffices that the joint probability distribution of a simultaneous measurement can be represented by the expectation values of a positive operator-valued measure.[16] It was demonstrated that, from the requirement on the joint probability distribution of the two observables that its marginals should reproduce the usual quantum mechanical single-observable distributions, it follows that the observables should correspond to commuting operators. This can be interpreted in the Bohrian way as a disturbance of the measurement of one observable by simultaneously measuring an incompatible one. Stated differently, we could say that the presence of the B_2 measuring instrument changes the probability distribution of any observable A_2 incompatible with B_2. Incidentally this means that our quantum mechanical theory of measurement is at variance with the principle of counterfactual definiteness(17) which attributes to A_2 the value it would have had if not B_2 but A_2 was actually measured. This principle does not take into account the disturbing influence mentioned above.

Returning now to the problem raised by Ruark, whether the A_1 measurement can be interpreted as an A_2 measurement, the answer to this question seems to be less inconclusive than it was to Ruark: it cannot be interpreted as such if, simultaneously with A_1 an observable B_2 is measured which is incompatible with A_2. This leaves open the possibility of such an interpretation if B_2 is compatible with A_2, or if there is no B_2 measurement at all, as is the case in the EPR proposal. In these situations there is no A_2 disturbing interference with particle 2, and the abovementioned objection does not apply. Indeed, as we shall see in the following, it is a matter of taste whether one chooses to accept the A_1 measurement in these situations as an A_2 measurement, or not.

2.5. Bohr between Realism and Instrumentalism

Before entering in detail on a discussion of the consequences of either choice, it might be fruitful to consider first the question of what is meant by saying that one bas measured observable A and obtained the result a_k. This question essentially concerns the interpretation of the quantum mechanical formalism. In the instrumentalist interpretation it means that a measuring instrument, known to measure observable A, has reacted to the preparation of an object by assuming a pointer position of some macroscopic indicator, which can be interpreted as the measurement result a_k. This should *not* be interpreted as a mere registration of a property of the object system. On the contrary, in the instrumentalistic view the quantum mechanical formalism merely describes how a macroscopic measuring instrument reacts to the macroscopic procedure by which the object system is prepared. As is well known, this view was strongly advocated by Heisenberg, who actually took it as a leading principle in deriving his uncertainty relations.(18) Also Bohr considered the quantum mechanical formalism to represent a purely symbolic scheme permitting only predictions,(19) a view which, incidentally, must not be identified with a denial of reality, as will become clear in the following.

The use of the term öbservableïs typical of a (positivistic) instrumentalist understanding of quantum mechanics. In axiomatic quantum mechanics observables are represented by self-adjoint operators. Bohr's completeness thesis can be expressed by the assertion that with every possible measurement in the atomistic domain there corresponds a self-adjoint operator.

Instrumentalism is opposed to realism in which, like in classical mechanics, the value of any measured variable is attributed to the object as a property which it possessed before the measurement. In this view a measurement is a means to give a (more) complete specification of the object as such, telling us something about the "reality" *between* preparation and measurement. This was Einstein's point of departure, which he tried to extend to quantum mechanics by introducing his element of physical reality. It should be stressed here that instrumentalism and realism are not incompatible. Indeed, it is very well possible to believe that a theory is about measurement results only, without denying the existence of an underlying reality that is not directly observed. I do not think that much is won by supposing that the moon is not there when nobody looks.[20] With Hooker[21] and Mermin[22] I think that a realistic attitude is preferable, even if this would imply the necessity to accept this reality to be nonlocal (Vigier[23]). Incidentally, in the following I will try to demonstrate that at this moment it is too early to yield to the appearance of nonlocality which is implied by Bell's derivation[24] of his inequalities. Before embarking on this topic, however, I want to try showing first that the positions of Bohr and Einstein with respect to reality are less irreconcilable than is often taken for granted.

Due to his instrumentalist attitude toward quantum mechanics Bohr has sometimes been considered (Hall[25]) as an idealist, *denying* the reality of unperceived objects. Hooker[26] criticizes Bohr on the grounds that the physical significance of the theory (quantum mechanics) is restricted greatly if not a realist view of theories is assumed. Hooker[21], however, also signalizes än unresolved ("Kantian") tension in Bohr's philosophy, among at least three positions with respect to the ontological issue of realism."Although Bohr tended to evade all talk about ontology and to remain on the epistemological level of interpretation of the languages of classical and quantum mechanics, Hooker also is aware of a tendency toward ä realist position which takes the macro and micro ontology's seriously and which, while attempting to preserve the Bohrian epistemological analysis, allows that we can achieve genuine knowledge of the intrinsic natures of macro and micro objects."

Bohr's realist attitude is also stressed by von Weizsäcker,[27] who comments on the controversy between Bohr and Einstein in the following way. According to von Weizsäcker it was a "tragic errorön Einstein's part to believe that Bohr was an instrumentalist so as to eliminate the notion of reality from physics. Although Bohr was rather reluctant to formulate anything that could appear as an ontology, according to von Weizsäcker[28] we can attribute to Bohr the views that "what can be described classically is a 'thing' in the commonsense meaning of the word- and "what is observed, certainly exists."Although quantum mechanics is only about phenomena, "Phenomena are phenomena about things."Indeed, Bohr's insistence on a description of the measurement conditions by means of *classical* concepts, and on the possibility of *defining* unambiguously attributes of physical objects *only* in the context of a specified experimental arrangement, strongly suggests that in the latter context we may think about the object in terms of realistic classical models. Thus, within the context of a position measurement with Bohr the object is a particle; if we measure interference fringes it *is* a wave.

It may have been this inclination toward realism that seduced Bohr into following EPR further in their presupposition of a really existing correlation than was necessary on strictly instrumentalist grounds. Bohr clearly had in mind a classical picture in which it is possible to use the classical law of momentum conservation if momentum is measured. Possibly, Bohr would have been more on his guard if EPR had advanced a wave function in which particle 1 momentum is correlated with particle 2 position, as for instance in

$$e^{ix_1x_2} = \int d\lambda\ \delta(x_1-\lambda)e^{i\lambda x_2} = \int d\lambda\ e^{i\lambda x_1}\delta(x_2-\lambda) \tag{3}$$

or, in Bohm's spin-version of the experiment,

$$\psi(1,2) = \frac{1}{\sqrt{2}}[\uparrow_z(1)\downarrow_x(2) - \downarrow_z(1)\uparrow_x(2)] = \frac{1}{\sqrt{2}}[\uparrow_x(1)\downarrow_z(2) - \downarrow_x(1)\uparrow_z(2)] \tag{4}$$

in which $\uparrow_z (1)$ stands for "spin up in the z-direction for particle 1,ëtc. Since no simple classical conservation laws are known for these situations, it would have been more difficult for Bohr to use his classical intuition as to the conservation of such correlations. If the quantum mechanical formalism can be reduced to the existence of an underlying reality it, indeed, is questionable whether this reality will be understandable in terms of the macroscopic notions of classical physics.

2.6. Toward a Reconciliation of Einstein and Bohr

Precisely because of Bohr's above-mentioned inclination toward realism it does not seem quite impossible to bridge, in a certain sense, the gap between the ideas of Bohr and Einstein, and to obtain a certain reconciliation, notwithstanding the seemingly rigid opposition of the opponents' stands. As we saw above, Bohr's position does not appear to be at variance with a certain kind of realism. We even have no reason to believe that Bohr would deny the possibility of an objectively existing reality that is not interacting with the observer. According to Petersen,(29) however, the crucial issue in Bohr's philosophy is not ontology. The core of Bohr's analysis is the emphasis on the *conceptual* character of the quantum problem. It is the conceptual issue of the *possibility of definition* of a property of an object in the atomic domain that is important to Bohr. The measurement arrangement plays an all-important role in this matter of definability. In our description of reality as it is experienced by us, we should realize that this reality is in interaction with a measuring instrument. *As far as quantum mechanics describes reality*, it refers to an *observed* reality, *not* to an objective reality of an isolated object system as Einstein would have it. According to Bohr, for this latter kind of system there is no possibility of definition of any property, and quantum mechanics does not describe this kind of reality. As a matter of fact, since it is necessary that the object interact with a measuring instrument if we want to obtain any knowledge about it, no theory about öbservables"can describe an *isolated* system.

Of course, it is impossible to achieve a complete reconciliation of Einstein and Bohr on the issue of the completeness of quantum mechanics. However, it is possible to approach the problem starting from a paradigm in which the two positions can be considered from a unified point of view, thus raising the discussion above the level of an unsatisfactory yes-no argumentation.

Bohr's completeness claim is incorporated in quantum mechanics by means of the idea that every possible measurement should correspond in a one-to-one fashion to a self-adjoint operator (öbservable"). Since the notion of measurement is not independently defined, we should be cautious not to be caught in the obvious circularity of defining "measurement"by means of the notion of öbservable,änd vice-versa. By doing so the possibility of considering some experimental procedure, *not* corresponding to a self-adjoint operator, as a *measurement*, is excluded *by way of definition*. Without an independent definition of the notion of "measurement,"quantum mechanics cannot be considered to be complete but in the tautological way of completeness on a domain of application defined by the theory itself. There is, however, no reason to suppose this domain to be any more universal than has turned out to be the case for all prior physical theories.

Without yielding to Bohr's completeness claim of quantum mechanics Einstein could have granted Bohr's contention that in the atomic domain there is an essential role for the measuring instrument, and that any theory describing an objective, unobserved readily would be about *un*observables. Viewed in this way, the Einstein-Bohr controversy is not a matter of principle. It is just about the domain of application of quantum mechanics. According to Bohr, quantum mechanics describes an observed reality, and Bohr's completeness claim, perhaps somewhat too hastily, restricts the possibility of defining properties of a system to these situations. Einstein, indeed, may be right in pointing at the possibility that we might obtain knowledge about a system exceeding the quantum mechanical knowledge. Bohr's quantum phenomenon may he unanalyzable in quantum mechanical terms. This, however, does not imply the impossibility of any theory, different from quantum mechanics, by means of which the quantum phenomenon could be analyzed. Somehow, the observation procedures used up to date seem to be well within the domain of quantum mechanics and interpretable in terms of Bohr's quantum phenomenon. However, this is no reason to stop trying to devise more penetrating observation procedures which will possibly lead us outside the domain of quantum mechanics. That the

EPR proposal remains well inside this domain, equally cannot be held against such a pursuit.

In conclusion, it does not seem impossible to bridge the gap between the ideas of Bohr and Einstein, be it only under the condition that the opponents' stands are not taken without a certain indulgence. Thus, Bohr's completeness claim cannot be maintained to its full extent as long as it cannot be proven that all microscopic processes are necessarily *quantum mechanical* measuring processes. On the other hand, Einstein's *objective* knowledge does not have a clear operational meaning, and hence cannot be attributed a very great importance. If, however, we adopt, with Bohr, the necessity to account for the interaction with the measuring instrument, and if, with Einstein, we insist on a detailed analysis of this interaction, then it does not seem improbable that the area of *observed* reality may be extended far beyond the domain of quantum mechanics. Even if our knowledge never will be knowledge of an *objective* reality which is independent of the way it is observed, from a physicist's point of view there is no reason to abandon completely the idea of such an objective unobserved reality. Within the domain of quantum mechanics, however, we should, with Bohr, explicitly take into account the interaction between object and measuring instrument. Within this domain Einstein's element of physical reality does not have any relevance because it does not correspond to a quantum mechanical observable, but refers to an unobserved reality.

3. MICROREALISM, THE PROJECTION POSTULATE

It is often felt that, although it is generally impossible to attribute a value of an observable to the object system, this should be possible if the state of the system is described by an eigenfunction of the observable. In this case a measurement of this observable yields with certainty the corresponding eigenvalue as its measurement outcome, thus suggesting that the object *possessed* this value *before* the measurement. Dirac's well-known requirement that a subsequent measurement of the same observable should yield with certainty the same value, then, also implies that the object should be in the same eigenstate *after* the measurement. This has lead to the idea that a measurement should be accompanied by a change of the wave function, known as the projection postulate.

The idea that an object system at every instant has a well-defined wave function (i.e., a pure state) also if it is a member of an ensemble that is described by a density operator (mixture), will be indicated as *microrealism* because it seems to me that it is a rudiment of the realism of classical mechanisms which has developed itself in the domain of quantum mechanics. It is to be distinguished from Bohr's realism as discussed above, because microrealism evidently makes its appearance in the quantum mechanical formalism whereas Bohr's realism is semiclassical. Also, with the latter a much more prominent role is attributed to the experimental arrangement in defining the reality of the object system. Yet, it seems to me that both kinds of (partial) realism have in common the tendency to exceed a purely instrumentalist interpretation of the quantum mechanical formalism. Evidently, the projection postulate stems from this tendency to transcend instrumentalism, although it is generally applied within a purely instrumentalist context.

3.1. Criticisms of the Projection Postulate

Margenau[8] has pointed out that the projection postulate is involved in the EPR proposal, and that, ïf it can be denied that in general a measurement produces an eigenstate, their conclusion fails, and the dilemma disappears."Indeed, the paradox stems from the simultaneous attribution to particle 2 of eigenfunctions of the *incompatible* observables, produced by means of projections which are due to measurements performed on particle 1. The same conclusion is reached by Cantrell and Scully,[30] who advocate as a solution to the EPR problem that particle 2 be described by the reduced density operator $\rho_2 = Tr_1\rho_{12}$, ρ_{12} being the density operator of the combined system, because ρ_2 reproduces the expectation values of all the observables of particle 2. Although the latter conclusion is completely correct, I do not think this solution to be totally satisfactory because ρ_2 no longer embodies the correlations between particles 1 and 2, which play an important role in the EPR problem and would be completely ignored by the Cantrell-Scully solution.

Yet, it seems to me that the Cantrell-Scully reasoning can easily be completed on the basis of a rejection of the projection postulate, if we stick more closely to the view that quantum mechanics is about measurement results only, and does *not* give a description of a reality (of particle 2) which is *not* observed by means of a measuring instrument that is directly interacting with the object system. This implies that quantum mechanics is held to yield no other predictions than merely the measured values and their relative frequencies of all possible observables A_{12} of the two particles, the observables A_1B_2 (A_1 and B_2 arbitrary) corresponding to a simultaneous measurement of observables A_1 and B_2 of particles 1 and 2, respectively. Note that in such measurements *always also* particle 2 is measured, thus implying the inapplicability of EPR's element of physical reality. Indeed, in a purely instrumentalist view of quantum mechanics the EPR problem is no real problem. Such problems only arise if the wave function is thought to describe the object itself instead of meter readings.

It should also be noted that this is *not* to vindicate Bohr's completeness claim of quantum mechanics. On the contrary, an instrumentalistic interpretation of quantum mechanics in no way implies the universality of its domain of application, but leaves open the possibility of measurements which are outside this domain. It also does not imply a denial of an underlying reality. However, if quantum mechanics refers only to measurement results, the reality corresponding to it is *not Einsteinian* *objective reality.* The reality of particle 2 may be influenced by the measurement performed on *this* particle and will be different in each of the following three circumstances: (i) measurement of A_2, (ii) measurement of B_2, (iii) no measuring instrument interacting with the second particle. Also from this reasoning it follows that it is not very convincing to use the projection postulate to describe "the"reality of particle 2 on measuring a correlated observable of particle 1, because the projection postulate does not distinguish between the three situations. On the other hand, this reasoning does not imply the impossibility of the projection postulate, because the latter's observational consequences might be compatible with any of the three circumstances.

3.2. Projection as a Kind of State Preparation

Within the ensemble interpretation of quantum mechanics it can be argued (Srinivas[31]) that the projection postulate could be awarded a proper meaning in terms of selection of subensembles. Thus, if a measurement of observable A is performed, with possible values a_j, the interaction between object and measuring instrument might be such that the subensemble of the particles yielding the value a_j can be described, after the measurement, by the corresponding eigenfunction of observable A. Indeed, such measurements, often called measurements of the first kind, seem to exist, although it is not difficult to produce examples of measurements *not* satisfying the above-mentioned property. Margenau,[32] in this respect, makes a severe distinction between measurements and state preparations, the projections being interpreted as state preparations due to the interaction with a measuring instrument and subsequent selection of a subensemble by the observer.

3.2.1. Impossibility of Observing Projection by Means of Direct Measurements. A similar reasoning can be applied in the EPR case. Here, by means of the A_1 measurement it seems possible to select subensembles of the correlated particle 2 ensemble, to the effect that these subensembles can be described by the corresponding eigenfunctions of A". Indeed, it is simple to demonstrate that a quantum mechanical measurement of any observable B_2, which is performed simultaneously with the A_1 measurement, yields results which are compatible with this kind of projection. This is precisely so, because in the correlated state (1) the conditional probability $p_\psi(b_i|a_j)$ of obtaining for B_2 the value b_i if for A_1 the value a_j is found, equals the probability $p_{\phi_j}(b_i)$ of getting b_i if the state of particle 2 is described by ϕ_j that is,

$$p_\psi(b_i|a_j) = p_{\phi_j}(b_i) \tag{5}$$

This can be verified by making use of the definition

$$p_\psi(b_i|a_j) = \frac{p_\psi(a_j, b_i)}{p_\psi(a_j)} \tag{6}$$

in which $p_\psi(a_j, b_i)$ represents the joint probability of a_j and b_i in a simultaneous measurement of A_1 and B_2, and $p_\psi(a_j)$ is one of its marginal distributions.

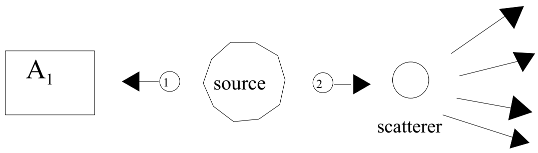
It should be stressed that within an *instrumentalist* interpretation of quantum mechanics the projection postulate does not do any harm. As long as the quantum mechanical state function ψ is interpreted to refer *only* to the measurement results of measurements that are actually performed, the equalities (5) and (6) guarantee that all measurement results of measurements A_1 and B_2 performed simultaneously on particles 1 and 2 are compatible with the projections $\psi \to \phi_j$. On the other hand, this also implies that, on this interpretation, the projection postulate is *superfluous* since all experimental evidence can be accounted for *without* assuming the projection to take place! Once again using Occam's razor, the instrumentalist is able to purge his theory by removing the projection postulate.

3.2.2. Impossibility of Observing Projection by Means of other Experiments. In a (micro)realist interpretation of quantum mechanics the wave function is thought of as describing in the first place the state of the object system itself instead of the measurement results. The wave function is interpreted to describe an objectively existing part of reality which is independent of any measurement performed in a causally disconnected region of space-time or to be performed in the future, although, of course, it can influence the outcomes of the latter kind of measurements. This, clearly, is what EPR had in mind when they required quantum mechanics to describe their ëlements of physical reality."Indeed, the EPR "paradoxïs due to the fact that quantum mechanics seems to attribute to the reality of particle 2 *different* wave functions, depending on what is measured in a causally disconnected part of space-time.

As discussed in Section 3.2.1, it is impossible to test by means of a *direct* measurement whether the reality of particle 2 is actually described by the projection postulate, because the measurement outcomes can be understood without projection. Are there other ways to probe whether the ensemble of particles 2 in the EPR problem is "really"split into subensembles by the measurement on particle 1? It might be thought that such ways *should* exist if the projection is to define an objective preparation procedure of a quantum mechanical (sub)ensemble, described by a state function which uniquely defines and is uniquely defined by the measurement outcomes of all possible measurements that can be performed on the (sub)ensemble. For instance, consider the EPR experiment in the version given by Bohm. In this experiment two spin-1/2 particles are prepared in the $S = 0$ state

$$\psi(1,2) = \frac{1}{\sqrt{2}}[\uparrow_z(1)\downarrow_z(2) - \downarrow_z(1)\uparrow_z(2)] \tag{7}$$

If the S_z-component of particle 1 is measured, the particle 2 ensemble is thought to split into two subensembles with spin up and down, respectively.



Figuur 3: Experimental arrangement for testing correlations in an indirect way.

We could try, now, to investigate whether this subdivision actually bas taken place by performing a spin-dependent scattering experiment with particle 2 in coincidence with an S_z measurement on particle 1. Although a *direct* measurement does not give any indication regarding this question, it might be hoped that more indirect measurements as the one depicted in Fig. 3 might do the job, since it is possible to measure the differential cross section for each subensemble, which, in general, are not identical. It, however, turns out that this does not work because the experiment can be reduced to the experimental situation of Eqs. (5) and (6) in which two observables A_1 and B_2 are measured simultaneously. As a matter of fact, if $B(\theta_2)$ is the set of scattering states $|b_2\rangle$ of particle 2 with scattering angle θ_2, and S_2 is the scattering operator, then the operator B_2 can be identified as the operator $\Sigma_{b_2 \in B(\theta_2)} S_2^+ |b_2\rangle\langle b_2| S_2$, and the whole experiment can be interpreted in terms of the joint probability

$$p(i_1, \theta_2) = Tr\rho P_{i_1} \Sigma_{b_2 \in B(\theta_2)} S_2^+ |b_2\rangle\langle b_2| S_2 \tag{8}$$

of measuring particle 1 with spin component i_1 (P_{i_1} being the corresponding projection operator) and observing particle 2 with scattering angle θ_2. More generally, any operation performed on particle 2 before measuring some observable B_2' can be described by means of a mimorphism[33] $\mathbf{T}_2$ changing the density operator ρ into the density operator $\mathbf{T}_2\rho$. Then, for the joint measurement of A_1 and B_2' we have

$$\langle A_1 B_2' \rangle = Tr(\mathbf{T}_2\rho) A_1 B_2' = Tr\rho A_1 \mathbf{T}_2^* B_2' = \langle A_1 B_2 \rangle \tag{9}$$

if we define $B_2 = \mathbf{T}_2^* B_2'$, B_2 being a self-adjoint operator if B_2' is. So, any measurement of this kind can be reduced to a direct measurement of observables A_1 and B_2, thus making any projection unobservable. Hence, even though projection as a kind of state preparation does not lead to any contradition, its assumption within the domain of quantum mechanics clearly has a metaphysical character. Since, as we shall see in Section 4, it has still other undesirable consequences, the projection postulate could better be discarded.

4. (NON)LOCALITY

4.1. Einstein's Inference of Nonlocality and Its Realist Roots

The early reactions to the EPR problem did not connect this problem with the issue of nonlocality. It was once again Einstein[6] who realized that Bohr's answer would imply a fundamental nonlocality if it is maintained that the description by means of the wave function is a complete one. In order to demonstrate this nonlocality, Einstein essentially used the reasoning which is peculiar to the projection postulate, to the effect that the wave function of particle 2 is determined by the measurement performed on particle 1. Since these particles are far apart and do not interact, a local measurement on particle 1 could only change the state of particle 2 if there would exist some nonlocal interaction. Since Bohr's completeness thesis rules out the possibility that particle 2 possessed values of incompatible observables simultaneously before the measurement, according to Einstein the only conclusion can be that completeness implies nonlocality.

A similar view is taken by d'Espagnat[34] who bases his principle of nonseparability on the existence of superluminal influences. d'Espagnat is aware of the realist roots of these superluminal influences, which according to him can only be incorporated in the theory if we choose a procedure "that relies quite heavily on the notion of attributes, or properties, of microsystems." Indeed, if we restrict ourselves to the purely instrumentalist notions of relative frequencies of measurement outcomes, the relative independence of distant measurements is incorporated in the theory by means of the principle of local commutativity (often called microcausality) which can be derived[7] from requirements to be satisfied by these frequencies only. So, in a purely instrumentalistic interpretation of the formalism of quantum mechanics there would seem to be hardly any reason for the assumption of nonlocality.

4.2. Criticism of Einstein's Nonlocality Inference

It should be stressed once more that on the level of measurement results -which is the relevant level for comparing experimental reality with quantum mechanics- there is no evidence of nonlocality as far as the principle of local commutativity has not been violated up till now. The reasons to assume that nature is basically nonlocal, as has been discussed up till now, were theoretical ones, stemming from the idea that quantum mechanics describes an objective, unobserved reality. If it is accepted with Bohr that this is not what is to be expected from quantum mechanics, but that this theory only describes an *observed* reality which is in interaction with a measuring instrument, then Einstein's nonlocality objection no longer holds ground. It seems to me that adherents of the Copenhagen interpretation would be too rash in granting Einstein his nonlocality inference because of the possibility to evade this conclusion by means of the improvement on Bohr's answer, discussed in Section 2.4.2. It need not be conceded that quantum mechanics describes a reality that is *not observed* by means of a measuring instrument interacting *directly* with it.

As was demonstrated in Section 3, the EPR reasoning hinges on the same kind of realism that is involved in the projection postulate. So does Einstein's inference of nonlocality. A rejection of the projection postulate, consequently, takes away the basis for this inference. In compliance with the principle of local commutativity and with the unobservability of any effect due to projection, no experimental evidence of nonlocality has ever been observed in performing local measurements. From the point of view of experimental reality the inference of nonlocality is as metaphysical as is the projection postulate.

This conclusion can even be arrived at without withdrawing into an instrumentalist attitude. We already saw that Bohr's point of view is not incompatible with a realism in which experimental reality is determined also by the measurement arrangement. In my opinion d'Espagnat(35) is not justified in reproaching Lochak(36) that trying to introduce Bohr's ideas into realistic (hidden variable) theories would be unmotivated and irrational. On the contrary, even though Bohr's philosophy did not in the least touch upon hidden variables theories, and although as we saw in Section 2.4, his reaction to the EPR challenge is liable to criticism, Bohr's general insight regarding the impossibility of neglecting the influence of the measurement arrangement in a microscopic measurement procedure is of a general importance not to be overlooked in any theory describing the microscopic domain, including hidden variables theories. If quantum mechanics describes only a reality that is in interaction with measuring instruments, it is pointless to confront quantum mechanics with the EPR situation in which only one particle is measured. The underlying reality described by the hidden variables theory may be different if different measurement arrangements are present, even if the preparation procedure (source) is the same. If projection is excluded from consideration, the EPR reasoning does not yield any reason to suppose that the reality of the particle 2 ensemble is determined also (or even exclusively?) by the measurement arrangement for particle 1. The foregoing analysis leaves open the possibility that quantum mechanics be reproduced by a local realistic (hidden variables) theory of a contextualistic nature in which the state of the object is determined locally by all preparing and measuring equipment that is or has been interacting locally with the object.

4.3. Criticism of Some Other Alleged Evidence of Nonlocality

Nowadays there is a rather general belief that the reality underlying quantum mechanics is essentially nonlocal. If the EPR reasoning does not imply nonlocality, this belief should be based on other data. The two most important of these are (i) Bohm's nonlocal quantum potential and (ii) the Bell inequalities. In the following I give a short discussion of both issues in order to demonstrate that also the inference of nonlocality from *these* data is not without its question marks, more elaborate discussions of these questions being in preparation.

(i) As regards the Bohm quantum potential it is important to note that Bohm's theory[37] is not a hidden variables theory underlying quantum mechanics, but only a reformulation of the Schrödinger equation, which has the appearance of a classical Hamilton-Jacobi equation. However, as will be demonstrated elsewhere, it is not possible to consider the variables $\mathbf{x}$ and $\mathbf{p} = \nabla S(\mathbf{x})$, figuring in Bohm's equations, as the simultaneous values of position and momentum of a particle. Hence, the conclusion that the nonlocality of the quantum potential can be reduced to the nonlocality of some underlying "classical" dynamics is not justified. The nonlocality of the quantum mechanical description which unquestionably becomes evident from Bohm's treatment might be reconcilable, as was already remarked by Bohm and Hiley,[38] with a *local* underlying field theory. The nonlocality of quantum mechanics possibly is not different from the nonlocality of equilibrium thermodynamics. In the domain of this theory no arbitrary local excitations are allowed that disturb the state of thermal equilibrium. It is clear that the physical basis of nonlocality in thermodynamics is not some nonlocal interaction or influence, but is situated in a restriction of the theory's domain of application to certain specified experimental circumstances. If quantum mechanics would describe only the *equilibrium* states of some underlying local field, the nonlocality of quantum mechanics could be explained in an analogous way. For the description of nonequilibrium states we would need a theory which is different from quantum mechanics, which might be local, and the restriction of which to equilibrium states should be equivalent with quantum mechanics.

In de Muynck[33] a distinction was drawn between the notions of macrolocality/causality and microlocality/causality, the formalism of quantum mechanics satisfying the former but not the latter. If quantum mechanics would describe only transitions between equilibrium states, the above-mentioned circumstance could be completely compatible with a relativistic subquantum dynamics. Violation of microcausality by the Schrödinger equation would be analogous with violation of causality by the solutions of the diffusion equation, which is not to be interpreted as a violation of relativistic causality by the underlying classical dynamics. The nonlocality of Bohm's quantum potential, then, should not be interpreted as an indication of the existence of a nonlocal interaction between distant particles. It just represents the correlation between different parts of the system, which is created by the relaxation to equilibrium.

(ii) As to the Bell inequalities there exists a widespread folklore to the effect that these inequalities should hold only for *local* hidden variables (h.v.) theories, thus implicitly leaving open the possibility that quantum mechanics might be compatible with some nonlocal h.v. theory. This folklore has its origin in Bell's original derivation[24] of the inequalities named after him. Inspired by the nonlocality of Bohm's quantum potential, Bell looked for evidence of an incompatibility of quantum mechanics with *local* realism. He found this incompatibility on the basis of the following scheme:

$$\text{hidden variables} + \ \text{locality} \rightarrow \ \text{Bell inequalities} \tag{10}$$

The locality condition was considered by him[24] to be a "vital assumption."This, however, is highly questionable. It can be demonstrated[39,40] that the Bell inequalities are properties of *any* Kolmogorovian probability theory, be it local or nonlocal. As a matter of fact, the Bell inequalities can be derived from the existence of a joint probability distribution (jpd) $p(A_1, A_2, B_1, B_2)$ for the values of the four observables $A_1,\ A_2,\ B_1$ and B_2 that are involved, if the jpd is assumed to satisfy the usual requirements of Kolmogorovian probability theory.

So,

$$\text{existence of jpd} \ \rightarrow \ \text{Bell inequalities} \tag{11}$$

We now see that Bell's locality assumption is not vital at all: if the hidden variables theory is assumed to be of the Kolmogorovian type, the existence of a Kolmogorovian joint probability distribution is guaranteed and the Bell inequalities follow *without* the assumption of locality, according to the scheme

$$\text{hidden variables} \rightarrow \text{existence of jpd} \ \rightarrow \ \text{Bell inequalities} \tag{12}$$

Comparison of (10) and (12) shows that the locality assumption in Bell's proof was superfluous.

5. CONCLUSIONS

In the formalism of quantum mechanics the relativistic idea of mutual nondisturbance of measurements which are performed in causally disjoint regions of space-time is introduced by means of the principle of local commutativity. There does not exist any experimental evidence of a violation of this principle. If quantum mechanics would correspond to a reality in which nonlocal influences or interactions occur, we would have to face the problem why this nonlocality does not have any experimental consequence for the probability distributions of local measurements which are performed simultaneously, as in the EPR-like experiments performed to test the Bell inequalities. Would it not look like a conspiracy if the nonlocal influences were constituted such that they only changed the *order* of individual measurement results without changing the relative frequencies, thus concealing their existence for the macroscopic observer? It should be stressed here that violation of the Bell inequalities in the above-mentioned EPR-like experiments is not acceptable as experimental evidence of nonlocality (cf. Section 4.3)!

In the foregoing sections the problem of (non)locality was studied both from an instrumentalist and from a realist point of view. It was demonstrated that a purely instrumentalist attitude does not give rise to any suspicion of nonlocality. Only if the quantum mechanical description is supposed to refer to an objective reality does the idea of nonlocality present itself. In particular the projection postulate, being a (micro)realistic rudiment in an otherwise instrumentalist interpretation, was seen to give rise to the inference of nonlocality.

Evidently, this inference is dependent on the interpretation of the formalism of quantum mechanics that is adopted. As far as different interpretations do not give rise to different values of the theoretical quantities to be compared with experiment, it is a matter of taste which interpretation one prefers to choose. Hence, if one prefers to live in a nonlocal world, one may choose the appropriate interpretation. In particular, the projection postulate was seen to do the job. On the other hand, if one is worried about the absence of any experimental evidence of nonlocal influences or interactions, it is equally well possible to choose an interpretation that does not give rise to nonlocality. Rejection of the projection postulate would be a necessary trait of such an interpretation.

Although in the absence of discriminating experimental evidence either choice is possible, it seems to me that it is by far more preferable to choose the second possibility. As long as there is no experimental evidence to the contrary, it seems wise to stick to a theory which does not deny the possibility of a world in which interactions are local. The other choice would confront us with the necessity to explain how it is possible that we do not observe any experimental trace of the nonlocal interactions, and why superluminal signalling is impossible notwithstanding the existence of superluminal influences (d'Espagnat[(35)]). By giving up the projection postulate which has no observable consequences, it is possible to remove also a nonlocality that in principle might be observable but that, actually, is not observed. If the redundancy of the projection postulate because of its unobservability is not a strong enough argument to expel this postulate from the foundations of quantum mechanics, its relation to the issue of nonlocality constitutes an additional argument against it that seems to be still more convincing. Essentially this argument was advanced by Margenau[(8)] already in 1936.

As is well known, the problem of (non)locality obtained its full weight only because of the attempts to supply quantum mechanics with a realistic basis in the form of a hidden variables theory reproducing the results of quantum mechanics. Most arguments advanced above against a nonlocality induced by the projection postulate also hold against the issue of a macrolocal quantum mechanics being reduced to a *nonlocal* hidden variables theory. Once again we should ask ourselves why this nonlocality would hide itself from observation.

Rather than trying to answer this question it seems appropriate to scrutinize the reasonings which have led to the conclusion that quantum mechanics can be reproduced only by a nonlocal hidden variables theory. The analysis of Section 4 demonstrates that this conclusion is far from being a compulsory one. It turns out that any h.v. theory, *either local or nonlocal*, satisfying the axioms of Kolmogorovian probability theory, obeys the Bell inequalities. Consequently, corroboration of quantum mechanics in EPR-like experiments, including delayed choice experiments like Aspect's switching experiment,[(41)] can be explained as a consequence of the fact that in the domain of quantum mechanics reality cannot be described by means of a Kolmogorovian probability theory. The Bell inequalities would be a consequence of locality only if they could be derived from it without the explicit or implicit assumption of Kolmogorovian probability.

At this moment it is not clear whether realism could be saved in some non-Kolmogorovian way. There have been discussed in the literature several proposals for a solution in this direction. Thus, by Bohm and Hiley,[(38)] Lochak,[(36)] and de Muynck et al.,[(42)] it is suggested that the measurement arrangement might play an important role in creating the reality of the object system. This essentially Bohrian assumption might make obsolete the existence of a joint probability distribution of the four observables involved in the Bell inequalities because these are not all measured simultaneously. An interesting possibility was also advanced by de Baere[(43)] to the effect that it might be impossible to prepare a system in two different experiments in precisely the same subquantum state, thus providing a physical basis for Lochak's idea of the "nonunicity of the hidden variables distribution." Also Pitowsky's[(44)] theory, based on nonmeasurable distributions, is worth considering, although the highly mathematical shape of the model makes it difficult to see its physical relevance. Todorov's[(45)] nonnormalizable probability density distributions are faced with an analogous difficulty, although this seems to me to imply more a stimulus to look for a physical interpretation of such concepts than a denunciation of such attempts to save in the first place realism and possibly even local realism.

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