Proc. Symposium on the Foundations of Modern Physics 1987, Joensuu, Finland, P. Lahti & P. Mittelstaedt, eds., World Scientific 1987

IS BOHM'S THEORY A NONLOCAL HIDDEN VARIABLES THEORY?

Willem M. de Muynck
Department of Theoretical Physics,
Eindhoven University of Technology
Eindhoven, The Netherlands

ABSTRACT

Three different kinds of hidden variables theories are discussed and compared with Bohm's theory. It is demonstrated that Bohm's theory does not satisfy the requirement that a reasonable account of the measurement process is given. The relation between the nonlocality issue of the Bell inequalities and Bohm's nonlocal quantum potential is discussed.

1. INTRODUCTION

One reason for Bell to doubt the validity of von Neumann's impossibility proof of hidden variables may have been the idea that Bohm's theory[1)] is yielding a counterexample to this impossibility thesis. As is well known Bohm's theory is completely equivalent with quantum mechanics, at least as far as experiments are concerned that fall within the domain of quantum mechanics. Hence, if Bohm's theory is a hidden variables theory von Neumann's proof cannot be correct. Once thus far, it was not difficult for Bell[2)] to prove the failure of von Neumann's proof.

The nonlocality of Bohm's quantum potential subsequently suggested a direction for Bell to look into in order to obtain his own impossibility proof. If Bohm's theory is a *nonlocal* hidden variables theory, such theories seem capable of being equivalent with quantum mechanics. Hence, at most *local* hidden variables theories seem to be excluded. This idea must have led Bell[3)] to the construction of the inequalities, named after him, which, in consonance with Bohm's ideas, are interpreted by the vast majority of physicists as a proof of the nonlocality of the quantum world.

The ideas of Bohm and Bell supplement each other in a very suggestive way. Consequently, when we resist the interpretation of the Bell inequalities as being due to a locality assumption[4], it seems necessary to contemplate also Bohm's theory from the same point of view.

2. BOHM'S THEORY

Point of departure of Bohm's theory is the possibility to write the Schrödinger equation

$$i\hbar \frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2m} \Delta\psi + V\psi \tag{1}$$

in a way that suggests a classical interpretation. If we put

$$\psi = R\, e^{iS/\hbar}, \quad R \text{ and } S \text{ real}, \tag{2}$$

then the following equations for R and S can be derived:

$$\frac{\partial P}{\partial t} + \operatorname{div}\left(P \frac{\vec{\nabla} S}{m}\right) = 0, \qquad P = R^2 \tag{3}$$

$$\frac{\partial S}{\partial t} + \frac{(\vec{\nabla} S)^2}{2m} + V + Q = 0, \qquad Q = -\frac{\hbar^2}{2m}\frac{\Delta R}{R} \tag{4}$$

Equation (3) is a continuity equation for the transport of the quantity $P = |\psi|^2$ if $\vec{\nabla}S/m$ can be interpreted as the local transport velocity. In the usual quantum mechanical interpretation this relation is interpreted as a law of probability conservation and expressed in terms of the probability flux

$$\vec{J} = \frac{i\hbar}{2m}(\psi^* \overleftrightarrow{\nabla} \psi - \psi\vec{\nabla}\psi^*) = P\,\frac{\vec{\nabla} S}{m}, \tag{5}$$

P being interpreted as a probability density.

It was the peculiar form of equation (4) that induced Bohm to propose a different interpretation, in which

$$\vec{p} = \vec{\nabla} S(\vec{x}) \tag{6}$$

is the "classical" momentum of the particle if the latter is situated at position $\vec{x}$. Indeed, equation (4) is the "classical" Hamilton-Jacobi equation of a particle acted upon by a potential V+Q. The extra quantum potential Q represents the deviation from purely classical behavior. It, hence, should describe the quantum mechanical fluctuations as embodied by the wave function $\psi(\vec{x})$. In Bohm's view the wave function is to be interpreted as a description of a real field acting on the particle. In later work[5] Q is indicated as a quantum *information* potential in order to point out that the quantum potential does not represent a mechanical force but should rather be considered as something like an "information content", to be compared with "radar waves that guide a ship".

The quantum potential has a nonlocal character. This becomes especially evident if the procedure of equation (2) - (4) is applied to the Schrödinger equation of two particles. Unless the two-particle wave function is a product of single-particle wave functions (which obtains if the particles are completely uncorrelated), the two-particle quantum potential seems to describe an interaction that does *not* vanish if the interparticle distance becomes infinite. The particles seem to influence each other however big their distance. Since, as is well known, it is impossible to use this nonlocality for superluminal signalling, as a first point of criticism it should be remarked that it is not explained by Bohm how it is possible that such nonlocal interactions do not lead to a violation of relativistic causality.

3. SOME OBJECTIONS AGAINST BOHM'S THEORY

An objection against Bohm's theory, already raised by Pauli[6] against a theory by de Broglie[7], is formulated by Einstein[8] as follows:

Consider a one-dimensional particle in an eigenstate

$$\psi(x) = A \cos kx \qquad (7)$$

of an infinite well potential. Then,

$$p = \frac{\partial S}{\partial x} = 0$$

contrary to the values $\pm \hbar k$ that follow from developing $\psi(x)$ into plane waves. More generally, it is clear that $\vec{\nabla} S = 0$ for a· · wave function $\psi(\vec{x})$ that is real-valued. An analogous objection was also raised by Rosen[9], who, for this reason, deemed a similar theory "hard to accept".

As a reaction to Einstein's objection Bohm[10] refers to his theory of measurement which "takes into account the disturbance of the observed system by its interaction with the measuring apparatus". The momentum measurement, then, should transform the wave function $\psi(x)$ "into a wave packet, with momentum approximately $+\hbar k$ or $-\hbar k$, and with equal probability of either result". Hence, the momentum measurement should transform the pre-measurement value $\vec{p} = 0$ into one of the post-measurement values $\pm \hbar\vec{k}$. The pre-measurement value $\vec{p} = 0$ cannot be measured within the quantum mechanical domain. All quantum mechanical measurements have this disturbing character, except, perhaps, position measurement, which seems to be interpretable as measuring the particle position without disturbing it.

The distinction between pre- and post-measurement values has been a severe reason for criticizing Bohm's theory because of the alleged metaphysical character of pre-measurement quantities[11]. I do not think that such criticisms are decisive, since, as also done in a reply[12] by Bohm, rightly can be referred to the possibility of future measurements falling outside the domain of quantum mechanics and yielding values that are closer to the pre-measurement ones than the quantum mechanical measurement results. For me, a more important point of concern is the fact that, in order to justify his theory of measurement, Bohm relies on a *quantum mechanical* theory of measurements of the first kind[1),13], in which the initial state Ψ_i of the combined system of object and measuring instrument

$$\Psi_i = \sum_n c_n \psi_n(\vec{x})\ f_o(\vec{y}) \tag{8}$$

is transformed by the measuring process into the final state

$$\Psi_f = \sum_n c_n \psi_n(\vec{x})\ f_n(\vec{y}), \tag{9}$$

$f_o(\vec{y})$ and $f_n(\vec{y})$ being initial and final "pointer" states of the measuring instrument, each final state corresponding with an eigenstate $\psi_n(\vec{x})$ of the measured observable. In the conventional interpretation this quantum mechanical theory of measurement is viewed upon as a reflection of Heisenberg's ideas[14)] with regard to quantum mechanical measurement, to the effect that the measurement process disturbs quantities that are incompatible with the observable that is actually measured, but the measured observable itself is not disturbed. This picture of what is going on in a measurement evidently is very different, and even incompatible, with Bohm's views. This difference is explicitly acknowledged by Bohm (ref. 1, p. 183). It is remarkable, then, and also a bit disturbing, that the relation between the pre-measurement value $\vec{p} = \vec{\nabla}S$ of momentum and the momentum value that is actually obtained in a momentum measurement, should be explained by means of a measurement theory that is developed according to a completely different, and even incompatible, picture of what is happening in a measurement process. Also, the pre-measurement value $\vec{p} = \vec{\nabla}S$ does not have a counterpart in the quantum mechanical theory of measurement processes of the first kind. What is clearly missing from Bohm's theory is a detailed account of the way the pre-measurement value of $\vec{p}$ is transformed into the quantum mechanical measurement result.

4. DIFFERENT INTERPRETATIONS OF QUANTUM MECHANICAL PROBABILITIES

In interpreting quantum mechanics we try to answer the question of the physical significance of the mathematical quantities obtaining in the theory. In this section I want to discuss possible meanings of the arguments of quantum mechanical probability distributions $W(a_i)$, in which the mathematical meaning of a_i is that of an eigenvalue of a selfadjoint operator representing a quantum mechanical observable. The question is: "What do we mean by saying that $W(a_i)$ is the relative frequency that observable A has the value a_i?", or analogous questions for the joint probabilities of several quantum mechanical observables.

In discussing *interpretations* of quantum mechanics we need not go beyond quantum mechanics. Any quantity to be encountered will, for this reason, be considered to be *a quantum mechanical quantity*, that is, some expectation value of a selfadjoint operator A:

$$\langle A\rangle = \mathrm{Tr}\ \rho\ A. \tag{10}$$

Here ρ is the density operator, representing a preparation procedure which, by definition, is in the domain of quantum mechanics. The expectation value is a linear functional of ρ. By the same token A represents a quantum mechanical measurement procedure. If

$$A = \sum_i a_i P_i,\ P_i P_j = P_i \delta_{ij}, \tag{11}$$

then the probability distribution $W(a_i)$ is given by a linear functional of the density operator,

$$W(a_i) = \mathrm{Tr}\ \rho\ P_i. \tag{12}$$

If $\{R_i\}$ is a set of positive operators satisfying

$$0 \leq R_i \leq I, \qquad \sum_i R_i = I, \tag{13}$$

then the linear quantities

$$q_i = \mathrm{Tr}\ \rho\ R_i \tag{14}$$

are quantum mechanical expectations obeying

$$0 \leq q_i \leq 1, \qquad \sum_i q_i = 1, \tag{15}$$

and , hence, are interpretable as probabilities. The set $\{R_i\}$ is called a positive operator valued (POV) measure, a projection valued measure $\{P_i\}$ being a special case. By means of POV-measures it is possible to define, *within the domain of quantum mechanics*, more general joint probability distributions

$$q_{ij} = \mathrm{Tr}\ \rho\ R_{ij}, \tag{16}$$

$$0 \leq R_{ij} \leq I, \qquad \sum_{ij} R_{ij} = I \tag{17}$$

than the ones traditionally encountered in quantum mechanics, the latter generally being represented as

$$W_{ij} = \mathrm{Tr}\ \rho\ P_i Q_j, \tag{18}$$

in which $\{P_i\}$ and $\{Q_j\}$ are projection valued measures satisfying $[P_i, Q_j] = 0$.

I shall now give a short discussion of several possibilities of interpreting the arguments of these probability distributions. In the following I shall distinguish two kinds of *realistic* interpretations and a *phenomanalist/instrumentalist* one.

The language of realistic interpretations is, like the language of classical mechanics, a language of properties. Properties refer to quantities that may be intrinsic (i.e. independent of the state of the object, like e.g. the rest mass of a particle), or extrinsic (i.e. dependent on the state of the object, like e.g. position and momentum of the particle, both liable to change with time). In classical mechanics a property generally is an *objective* property, that is, a property that can be attributed to the object independently of its surroundings. This, essentially, implies that the object is considered to be isolated from the rest of the world (apart perhaps from certain fields that are taken into account as parameters in the Hamiltonian).

Sometimes properties seem to be attributable to the object only if this object is situated in certain environments or contexts. For this reason it seems necessary to take into account also the possibility of *contextual* properties the value, or even the existence, of which depends on the environment. In quantum mechanics this environment is determined by the preparation and measurement set up. A contextual quantity does not have an unambiguous meaning, but depends on the measurement procedure. Not only its measured value is dependent on this procedure, but even the *definition* of the measured quantity may depend on it. Thus, the measured value may be associated with either the *final* value of the contextual quantity (i.e. *after* completion of the measurement) or with some average value obtained by averaging over the measuring process. What is essential, here, is that the value a_i

of the observable A can be attributed to the object only as far as the object is influenced by the measurement arrangement.

The language of instrumentalist/phenomenalist interpretations is a language of phenomena. Phenomena are often introduced[15], in the context of empiricism, as "observable phenomena" or "appearances" in order to represent the *empirical* substructures of a theory. For the present purpose it suffices to characterize a phenomenon as an *observable* part of reality. Within the domain of classical mechanics, any property can be considered to be observable. Hence, within the domain of classical mechanics every phenomenon can be taken to correspond to a property of the object itself: the classical world is observed "as it is". The event of a macroscopic particle having velocity $\vec{v}(t)$ at time t is both a property of the particle, *and* a phenomenon in case this property is actually observed.

The situation is different in microphysics because here a macroscopic measuring instrument acts as an intermediary between object and observer. The observer has only access in a direct way to the measuring instrument, not to the object system. Therefore the phenomenon should be attributed as a property to the measuring instrument rather than to the object. Thus, a track in a Wilson or bubble chamber is a phenomenon playing a role in the detection of an elementary particle. The track consists of a great number of small droplets or bubbles, the development of which is caused by a particle crossing the chamber. For this reason the track provides us with information about the particle. However, it is not a property of the particle itself, but should be considered, - in the sense of classical mechanics - , as a property of the chamber. Although the existence of a particle trajectory is made highly plausible by the existence of the track, the track may not be identified with the trajectory. Actually, the same track could be caused by many different trajectories!

A pure phenomenalist/instrumentalist interpretation considers quantum mechanics as a theory about measurement results of quantum mechanical measurements, without any necessity to attribute the measurement result to the object itself. The theory just yields predictions abou .he reaction of certain macroscopic measuring instruments if certain macroscopic preparation procedures are performed. Then, the quantum mechanical probabilities are just probabilities of measurement results, i.e. of properties of the measuring instruments.

In retrospect, we can distinguish three possible interpretations of the argument a_i in a quantum mechanical probability distribution $W(a_i)$:

1) a_i is an objective property of the object,

2) a_i is a contextual property of the object,

3) a_i is a phenomenon, i.e. a property of the measuring instrument.

5. PROBABILITY DISTRIBUTIONS IN HIDDEN VARIABLES THEORIES

If it is assumed that quantum mechanics can be reproduced by means of a realistic (hidden variables) theory, this classification yields different representations of quantum mechanical probabilities. Let Λ denote the configuration space of hidden variable λ, and $\rho(\lambda)$ its probability distribution. Then, in the objectivistic case 1 we can write

$$W(a_i) = \int_{\Lambda_i} d\lambda \; \rho(\lambda) = \int_{\Lambda} d\lambda \; \chi_{\Lambda_i}(\lambda) \; \rho(\lambda), \tag{19}$$

in which Λ_i is the subset of Λ for which $A(\lambda) = a_i$ and $\chi_{\Lambda_i}(\lambda)$ is the indicator function of Λ_i. It should be noticed that, as far as the hidden variables theory is intended to reproduce quantum mechanics and $\rho(\lambda)$ is thought to represent a quantum mechanical state, the probability $W(a_i)$ should also be expressible as a linear functional (12) or (14) of a density operator. A general hidden variables theory, however, might have a wider scope, and contain expressions of the form

(19) that are not expressible as linear functionals of a density operator. Moreover, (19) might refer to properties that do not correspond with quantum mechanical observables.

In the contextualistic case (case 2) we take into account the possible influence of the detection process on the resulting probability. This can be done by introducing a stochastic operator[16)] $\mathcal{T}_\lambda$ which transforms $\rho(\lambda)$ into a new probability distribution, thus yielding

$$W(a_i) = \int_{\Lambda_i} d\lambda\ \mathcal{T}_\lambda \rho(\lambda) = \int_{\Lambda} d\lambda\ \rho(\lambda)\ \mathcal{T}^*_\lambda\ \chi_{\Lambda_i}(\lambda), \tag{20}$$

$\mathcal{T}^*_\lambda$ being the adjoint of the stochastic operator $\mathcal{T}_\lambda$. If we write

$$p(a_i|\lambda) = \mathcal{T}^*_\lambda \chi_{\Lambda_i}(\lambda), \tag{21}$$

we can interpret $p(a_i|\lambda)$ as the conditional probability of a_i for given λ. This quantity, evidently, depends on the measuring process. Sometimes it is assumed that $W(a_i)$, nevertheless, can be attributed to the object as an objective property. This would be reasonable if there would exist only one single procedure to measure observable A. We might call this the *quasi-objectivistic* case. Even then, however, it would not be allowed to attribute $W(a_i)$ to the object in a context that is different from this single measurement context.

If we want to take into account explicitly the interaction between object and measuring instrument we should extend the description to include the space M_A of the hidden variables μ of the measuring apparatus for observable A. Introducing the stochastic operator $\mathcal{T}^A_{\lambda\mu}$ describing this interaction, we obtain for the contextualistic case

$$W(a_i) = \int_{\Lambda_i} d\lambda \int_{M_A} d\mu\ \mathcal{T}^A_{\lambda\mu}\ \rho(\lambda)\ \rho_A(\mu), \tag{22}$$

$\rho_A(\mu)$ being the initial probability distribution of the hidden variable of the measuring instrument. This expression can be reduced to

$$W(a_i) = \int_\Lambda d\lambda \quad p(a_i|\lambda)\ \rho(\lambda), \tag{23}$$

with

$$p(a_i|\lambda) = \int_{M_A} d\mu\ \rho_A(\mu)\ \mathcal{T}^{A*}_{\lambda\mu}\ \chi_{A_i}(\lambda). \tag{24}$$

So, introducing the dynamics of the measurement interaction does not yield much news over the case of equation (20) in which the dynamics of the measuring apparatus is not taken into account explicitly.

The instrumentalist/phenomenalist case, finally, is represented by the expression

$$W(a_i) = \int_\Lambda d\lambda \int_{M_{A_i}} d\mu\ \mathcal{T}^{A}_{\lambda\mu}\ \rho(\lambda)\ \rho_A(\mu) \tag{25}$$

which differs from (22) in the boundary of the domain of integration, M_{A_i} being the subset of M_A the apparatus finally is in if the final state is to be interpreted as the measurement result a_i. Although, also here, it is possible to write (25) in the form (23), with

$$p(a_i|\lambda) = \int_{M_A} d\mu\ \rho_A(\mu)\ \mathcal{T}^{A*}_{\lambda\mu}\ \chi_{A_i}(\mu) \tag{26}$$

($\chi_{A_i}(\mu)$ being the indicator function of M_{A_i}), there is a fundamental difference with the other cases: it is now impossible to attribute the probability $W(a_i)$ to the object system as an objective property, since the probability evidently only exists if the measuring instrument is present.

6. BOHM'S INTERPRETATION

I shall now try to answer the question which of the three interpretations is applicable to Bohm's theory. The problem here is that not all assertions in the articles by Bohm and coo ators are equally clear. Some even appear to be inconsistent. Thus, in a recent review article[5b)] we read the following: "We feel that these examples are sufficiently broad in their applications to indicate how the ontology works out more generally, and to enable us to understand individual quantum processes *without having to bring in measurement*" (p.324, my italics). This suggests that the quantities should be considered as objective properties of the particle (case 1). This is also apparent from p. 325 where the probability density of position is interpreted as "the probability density for the particle to *be* at a certain position" (their emphasis), and where is stated explicitly that "here we differ from Born who supposed that it was the probability of *finding* the particle there in a suitable measurement" (their emphasis). This, in any case, seems to exclude the third, instrumentalist/phenomenalist interpretation.

Bohm is well aware of the important role the measuring apparatus plays in the measurement process. As he puts it in the second part of ref. 1: " Observables are not properties belonging to the observed system alone, but instead potentialities whose precise development depends just as much on the observing apparatus as on the observed system". This points into the direction of the second, contextualistic interpretation. Indeed, Bohm distinguishes the pre-measurement value $\vec{p} = \vec{\nabla}S$ of momentum (he calls this the "actual" value) from the value obtained in a quantum mechanical measurement. As already discussed before these are different in general. Whereas the probability distribution of the measured values is given by the usual quantum mechanical expression

$$W(\vec{p}) = |a(\vec{k})|^2 = \mathrm{Tr}\,\rho\, P_{\vec{p}}\,, \quad P_{\vec{p}} = |\vec{k}\rangle\langle\vec{k}|,\ \rho = |\psi\rangle\langle\psi|,\ \vec{p} = \hbar\vec{k} \qquad (27)$$

$a(\vec{k})$ being the Fourier transform of $\psi(\vec{x})$, the probability of the actual value of momentum seems to be derivable from $\psi(\vec{x})$, using (6), as

$$W_{act}(\vec{p}) = \int_{\vec{\nabla}S(\vec{x})=\vec{p}} d\vec{x}\,|\psi(\vec{x})|^2 \qquad (28)$$

the integration being restricted to that part of configuration space for which $\vec{\nabla}S(\vec{x}) = {}^{\rightarrow}$ Indeed, for real-valued $\psi(\vec{x})$ this part amounts to the whole space for $\vec{p} = 0$, and vanishes for $p \neq 0$, in accordance with previous results. On the other hand, for real $\psi(\vec{x})$ the probability distribution (27) is only restricted by the relation

$$a(\vec{k}) = a^*(-\vec{k}). \tag{29}$$

This, evidently, does not imply $W(\vec{p})$ to vanish for $\vec{p} = \hbar\vec{k} \neq 0$.

It, incidentally, should be remarked that the probability distribution $W_{act}(\vec{p})$ does not have a quantum mechanical representation of the form (12). Formally, (28) can be written as an expectation value of a projection operator, viz. the one projecting a wave function $\varphi(\vec{x})$ according to

$$P'_{\vec{p}}\ \varphi(\vec{x}) = \chi_{\vec{p}}(\vec{x})\ \varphi(\vec{x}), \tag{30}$$

$\chi_{\vec{p}}(\vec{x})$ being the indicator function of the region of configuration space for which $\vec{\nabla}S(\vec{x}) = \vec{p}$. However, now $P'_{\vec{p}}$ depends on the wave function $\psi(\vec{x})$, thus causing (28) to deviate from linearity. Evidently, if the "actual" value $\vec{p} = \vec{\nabla}S(\vec{x})$ is interpreted in the way Bohm proposes, then it can not be viewed as a quantum mechanical quantity. This need not bother us too much, because it is possible to deny the status of a quantum mechanical quantity to quantities having values that can be interpreted as *pre*-measurement values. This would be tantamount to saying that not the objectivistic probabilities (19) but the contextualistic ones (23) should reproduce the quantum mechanical probabilities in case the preparation and measurement procedures are within the domain of quantum mechanics. This is a perfectly reasonable position. On the other hand, as stated before, without a measurement theory relating "actual" and measured values of a quantity, it is rather arbitrary to declare the result of any algorithm, however suggestive this algorithm may be, as the "actual" value of a quantity.

One of Bohr's leading principles in guessing the generalisation of classical mechanics into the domain of quantum mechanics was the correspondence principle. The validity of this principle induces certain similarities between the different theories. Bohm's representation of the Schrödinger equation is a clear manifestation of this similarity. Another manifestation is Ehrenfest's theorem yielding still another way to represent quantum mechanics in a manner that is very suggestive of classical mechanics. Both representations are mathematically equivalent with the Schrödinger equation. Since nobody seems to deny that the latter equation describes *only* statistical properties of the quantum world, we should have solid arguments if we want to interpret essentially the same mathematics in a different way. In fact, we have not. On the contrary, as indicated in equation (5), the quantity $\vec{\nabla}S$ has, in the "usual" interpretation, a *statistical* meaning which, in principle, lends itself to experimental verification. The equality $\vec{p} = 0$, obtaining for real-valued wave functions, can be interpreted as the, in principle observable, *statistical* result that the probability flux $\vec{J}$ vanishes, consistent with the vanishing of the quantum mechanical expectation value $\langle\vec{p}\rangle$ resulting from (29). It does not seem to be very reasonable to suppose that the same mathematical quantity has still another, completely different meaning, viz. that of a pre-measurement value. This is not to deny the possibility that a particle may have an "actual" momentum value. It, however, appears to be very improbable that this value can be derived from an approvedly statistical theory like quantum mechanics. For this reason an interpretation of Bohm's theory as yielding "actual" pre-measurement values is hardly plausible.

Analogous remarks can be made with respect to the nonlocality of the quantum potential. If this is interpreted as a nonlocal interaction, we are confronted with the problem of explaining the principle of local commutativity in quantum mechanics which is an expression of the mutual nondisturbance of quantum mechanical measurements performed at a space-like distance from each other. It remains completely unclear why such a nonlocal interaction would be contrived in such a way that in EPR-like experiments the probability distribution of one observable is not disturbed by the other measurement. Why does this nonlocal interaction hide itself from detection?

Such problems disappear if it is realized that the quantum potential formalism is equivalent with the wave function formalism and, hence, should encompass the same experimental information, i.e. probabilities like the ones given in equations (12)-(18) and the expectation values calculated from them. More specifically, the joint probability distributions of EPR-like measurements are described by (18) if $\{P_i\}$ and $\{Q_j\}$ are two spectral representations of observables of each of the particles separately. Unless the density operator ρ can be written as a product $\rho_1\rho_2$ of two single-particle density operators the particles are said to be statistically correlated. It is interesting to observe that precisely under this circumstance of statistical correlation the nonlocal character of the quantum potential becomes manifest. For this reason it is rather natural to view the nonlocality of the quantum potential as an expression of the statistical correlation between distant particles. Since such correlations can always be understood from a common preparation process there is no nonlocal interaction involved. It is even misleading to speak about *nonlocal* correlations because the correlation can readily be explained in terms of local interactions being effective when the particles were near each other.

Since the Bell inequalities are often invoked to disprove the possibility of the picture presented here, this issue is discussed in the next section.

7. RELATION WITH THE BELL INEQUALITIES

After the derivation of the Bell inequalities EPR-like experiments generally have been analyzed in terms of these inequalities. Although it is doubtfull whether this is the most appropriate way to do such an analysis[17),18)], in the present context I will follow the same route. It is a widespread belief that the Bell inequalities are due to a locality assumption.

Consider EPR-like measurements performed on a system of two particles, A_1 and B_1 being incompatible observables of particle 1 and analogously A_2 and B_2 for particle 2. By Rastall[19)] it was demonstrated that, under the assumption of macrolocality[17], for the validity of the Bell inequalities it is necessary and sufficient that a joint probability distribution (jpd) exists of the four observables that are involved. If such a jpd exists it is impossible that the measurement results of all EPR-like experiments can be derived from it by taking marginals. Evidently, such a jpd does not describe the quantum world.

By Dieks[20] the nonexistence of such a jpd is interpreted, once again, as a consequence of nonlocality: since the value of observable A_2 may, because of nonlocality, depend on the circumstance whether we measure A_1 or B_1 on the other particle, it is impossible to attribute simultaneously a well-defined value to A_1, A_2 and B_1.

Although this reasoning, taken by itself, is not incorrect, it is not very relevant because also in case of locality such a jpd cannot exist. This is so, because the existence of the jpd of the four observables does not only imply the existence of jpd's of pairs of *compatible* observables (which can be compared with the outcomes of EPR-like experiments), but also of pairs of incompatible observables, like, for instance, $p(A_1 = a_i^1, B_1 = b_j^1)$. According to Heisenberg's disturbance theory of measurement this is impossible if both marginals of this expression have to yield undisturbed probabilities. For this reason, it is possible to attribute the nonexistence of Rastall's jpd, to the Heisenberg measurement disturbance of the incompatible observable B_1 if A_1 is measured (and vice versa). Since A_1 and B_1 are observables of the same particle, no nonlocality is involved.

In comparing the implications of the three possible interpretations considered in section 5 with respect to the existence of a jpd, it is clear that for EPR-like measurements the instrumentalist/phenomenalist interpretation does not lead to such a jpd because of the necessity, in this interpretation, to measure the four observables jointly. Also, since in the objectivistic realistic case the quantities are attributed to the object independently of the measurement procedure, this interpretation cannot lead to the quantum mechanical results. For this reason the contextualistic realistic case remains as the only realistic possibility. Bohm and Hiley[21)] arrive at a comparable conclusion in their attempt "to explain quantum mechanical nonlocality along Einstein's lines, i.e. in terms of a local field". They come to the conclusion that Bell's inequalities cannot be derived if the hidden variables probability distribution $\rho(\lambda)$ is dependent on the measurement setup.

From the foregoing it is, indeed, clear that contextualism is necessary for a realistic understanding of quantum mechanics. However, an unqualified contextualism may not be sufficient. As a matter of fact, also in the contextualistic case, in which $p(a_i|\lambda)$ depends on the measurement procedure, it is possible to write down a jpd according to

$$p(a_i^1, a_j^2, b_k^1, b_l^2) = \int d\lambda\ \rho(\lambda)\ p(a_i^1|\lambda)\ p(a_j^2|\lambda)\ p(b_k^1|\lambda)\ p(b_l^2|\lambda) \qquad (31)$$

from which the single-observable probabilities (23) can be obtained by marginalization, and which satisfies macrolocality. Hence, the Bell inequalities are satisfied even in this contextualistic case.

However, the jpd (31) does not seem to represent the physical situation of EPR-like experiments because it does not allow for the possibility that e.g. the probability distribution of A_1 might differ in the context of a B_1-measurement from the distribution of A_1 in the context of an A_1-measurement. The construction of the jpd (31) is, evidently, based on an unwarranted quasi-objectivism (cf. sect 5). The lack of a realistic theory of measurement disturbance makes it impossible to estimate whether Bohm's theory excludes such quasi-objectivistic jpd's. In any case, they are excluded by the traditional Heisenberg theory of measurement, which, therefore, seems to me to have a certain advantage over Bohm's theory, even if we try to come to a realistic understanding of quantum mechanics.

8. CONCLUSION

My conclusion is that Bohm's theory, as it stands, should not be considered as a hidden variables theory, but as a suggestive way to write down the Schrödinger equation. For this reason, Bohm's theory should not be interpreted as yielding information transcending the quantum mechanical one. Far from representing a nonlocal interaction the nonlocality of the quantum potential can be interpreted as descriptive of a correlation between the particles, which may be caused by the preparation process and which need not vanish when the particles separate.

The basic idea of Bohm's theory is, to consider quantum mechanical states as a kind of equilibrium states of some subquantum dynamics. This idea is very attractive and is worth to be developed further, both as an explanation of the quantum riddle and as a source of inspiration in finding ways to transcend the experimental domain of quantum mechanics. It is questionable, however, whether this will be possible by sticking to a disguised form of the Schrödinger equation and a rather arbitrary interpretation of the mathematical formalism. Admittedly, it is impossible to present a falsification of the interpretation, mainly because it does not offer a sufficiently developed theory of measurement to be able to draw even the most general conclusions like the ones necessary to investigate whether the Bell inequalities are satisfied or not. As Heisenberg's theory of measurement is developed not much further, it remains possible to prefer Bohm's measurement scheme over Heisenberg's one. For this reason it is, at this moment, not strictly impossible to view Bohm's theory as a hidden variables theory.

On the other hand, several arguments were advanced in the foregoing which make such a choice unattractive. Among these arguments the nonlocality issue is not the least important one. Indeed, we should have strong indications of the correctness of the theory, if we are to accept the consequence of a theoretical nonlocality that has no counterpart in experimental physics. Such indications we do not have, at least not if we resist the temptation to justify the nonlocality of Bohm's theory by pointing to the Bell inequalities, while referring to Bohm's theory in justifying the role of the locality assumption in the derivation of the Bell inequalities. Hence, unless we accept, without any necessity, Bohm's theory as a hidden variables theory, we are not constrained to believe that we live in a nonlocal world.

By renouncing an interpretation of Bohm's theory as a hidden variables theory I do not intend to deny the possibility of a realistic interpretation of quantum mechanics. On the contrary, if we want to transcend the experimental domain of application of quantum mechanics, such a realistic interpretation may be very helpful in finding new theories and new phenomena. It seems to me that a nonlocal theory like Bohm's one could only contribute to this goal if it would predict experimental evidence of this nonlocality. As long as the theory is completely equivalent with quantum mechanics this, however, will fail because of the quantum mechanical principle of local commutativity. For this latter reason Bohm's theory has to provide for an explanation why the nonlocality on the subquantum level does not manifest itself on the level of quantum phenomena. Far from providing an explanation of macrolocality it introduces a nonlocality that is of a completely metaphysical nature. For this reason it seems to be more of a hindrance to the attempt of finding a realistic interpretation of quantum mechanics, than a step forward into this direction, even though it contains quite a lot of seminal ideas. As demonstrated above, the locality issue is not the relevant issue in assessing the importance of the Bell inequalities. If the disturbance of the object system by the measurement interaction is duly taken into account it does not seem impossible to give an interpretation of quantum mechanics in realistic terms that is basically local. As far as Bohm's theory hampers attempts to develop such a theory its influence seems to be that of a degenerative rather than a progressive research program. This contribution has the intention to help to try to improve on this state of affairs.

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