On Realism and Quantum Mechanics

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Abstract. A discussion of the quantum mechanical use of superposition or entangled states shows that descriptions containing only statements about state vectors and experiments outputs are the most suitable for Quantum Mechanics. In particular, it is shown that statements about the undefined values of physical quantities before measurement can be dropped without changing the predictions of the theory. If we apply these ideas to EPR issues, we find that the concept of non-locality with its ‘instantaneous action at a distance’ evaporates. Finally, it is argued that usual treatments of philosophical realist positions end up in the construction of theories whose major role is that of being disproved by experiment. This confusion proves simply that the theories are wrong; no conclusion about realism (or any other philosophical position) can be drawn, since experiments deal always with theories and these are never logical consequences of philosophical positions.

1 Introduction

The question of the (im)possible coexistence between realism and Quantum Mechanics goes back to the birth of the latter; however, the addressed issues and the relevance given to them have changed since then. The debate has shifted from the discussion of the epistemological status of Quantum Mechanics to specialized topics connected with the so called EPR paradox [1]: the turning points have been the paper by Bell on his inequalities [2] and the Aspect’s experiment on EPR correlated photons pairs [3].

Fuchs and Peres hold that ‘Quantum Mechanics needs no interpretation’ [4]. This statement is equivalent to say, as we do in the abstract, that ‘descriptions containing only statements about state vectors and experiments outputs are the most suitable for Quantum Mechanics’. In the following, we shall use the term ‘interpretation’ in two senses. Given a physical description based on a set of equations, there is a ‘minimal (and necessary) interpretation’: it tells us which are the procedures for measuring (at least some of) the
physical quantities that appear in the equations. The usual interpretation of Quantum Mechanics is based on a ‘second level’ interpretation characterized by the assumption that ‘in some instances, the physical quantities of a system do not have a definite value before measurement’. It will be shown that this assumption can be dropped without changing the predictive content of Quantum Mechanics.

The philosophical background of the main thesis sustained in this paper may be defined as a ‘tempered’ realist one. However, since the thesis of this paper, though suggested by this philosophical position, does not logically depend on it, we omit its illustration. The interested reader can see [5].

2 Realism and Quantum Mechanics

Since Quantum Mechanics makes statements about the World, it is a realist description in the following sense:

- it is interpreted on the basis of, at least, the basic realist assumption: ‘there is an external World whom the observer belongs to’;
- it describes experiments and uses experimental reports: descriptions and reports of experiments are realist discourses.

2.1 The superposition state

As a basic case, let us consider a two states system $S$ described by the state vector:

$$|\psi> = \frac{1}{\sqrt{2}} (|\psi_1> + |\psi_2>)$$

where 1 and 2 label the two states of $S$ (the factor $1/\sqrt{2}$ implies that the two states are equally probable). Let us further suppose that the eigenvalue of a physical quantity $A$ of the system described by the eigenvector $|\psi_1>$ is $a_1$ and, correspondingly, $a_2$ for $|\psi_2>$. Here are two possible interpretations of equation (1):

(S1) The system $S$ is described by the state vector (1). If a measure of the physical quantity $A$ is made on the system $S$, then the probability of finding $a_1$ or $a_2$ is $1/2$. This is a ‘minimal’ interpretation.
(S2) The system $S$ is described by the state vector $|\Pi\rangle$. The physical quantity $A$ does possess, before the measurement, neither the value $a_1$ nor the value $a_2$; during the measurement, the system passes from the 'superposition state' to the state $|\psi_1\rangle$ or $|\psi_2\rangle$ with the associated properties [statement (M2): from 'The physical quantity $A$... ' to the end]. (M2) is a realist assertion because it affirms something about the World; moreover, since it is implicitly considered as experimentally not testable, it is a metaphysical statement. This interpretation is of 'second level', because of statement (M2).

The predictions of Quantum Mechanics depends only on the form of the state vector $|\Pi\rangle$. (M2) is not used in the deduction chain that leads to experimentally testable predictions: it can be dropped without changing these predictions. As a matter of fact (M2) is used only in the interpretation of experimental results. (S2) leads directly to Schrödinger’s ‘cat paradox’, to all its variations and extravagant implications. With (S1), instead, we shall avoid any trouble.

As a second example, let us consider a beam of linearly polarized light coming out from a polaroid whose axis is, say, along the $x$ axis. If the beam is falling on a second polaroid whose axis $x'$ is tilted by an angle $\theta$ from that of the first polaroid, Quantum Mechanics predicts that each photon has probability $\cos^2 \theta$ of passing through the second polaroid $|1\rangle$. Quantum Mechanics does so by describing the incoming photon by a ‘superposition’ of linear polarizations along two perpendicular directions $x', y'$:

$$|x\rangle = |x'\rangle \cos \theta + |y'\rangle \sin \theta$$  \hspace{1cm} (2)

The experiment can be described in the following way. The photon impinging on the second polaroid is linearly polarized along $x$ since it has passed the first polaroid. This statement derives from the operational definition

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1. Also classical electromagnetism yields the same prediction if we assume that the probability of traversing the second polaroid is proportional to the classical predicted intensity of the light passing the second polaroid. Similarly, in the case of the two slits experiment, classical electromagnetism can predict what is the probability for a photon to reach a point on the screen, if it is assumed that this probability is proportional to the classical light intensity predicted for that point. Of course, this is an ad hoc adjustment of Maxwell’s theory; however, it is conceptually interesting. For a detailed discussion, showing also that even classically it is not possible to say which is the energy path between the slits and the screen, one might see \[6\].

2. Also classical electromagnetism does, of course, a similar thing with the electric field.
according to which a photon is said to be ‘linearly polarized along $x$’ if it has passed a polaroid oriented along $x$. Taking into account the type of experimental apparatus, we describe the photon by equation (2); the photon coming out from the first polaroid has probability $\cos^2 \theta$ of passing through the second one. The interaction between the photon and the polaroid changes the polarization of the photon.

On the basis of equation (2), no one would hold that the photon does not possess a definite polarization before the second measurement (we know it is polarized along $x$): nevertheless, we describe the photon by a ‘superposition’ state vector. This means that the photon under study can be described by a superposition state vector even when it has a definite value of the polarization. Equation (2) is clearly written down by having in mind, as in the classical treatment, the type of experiment we are performing (the impact with the second polaroid).

### 2.2 EPR issues

The debate addresses (at least) four issues: realism, locality, causality and completeness of Quantum Mechanics. Historically, the starting point has been the problem of completeness of Quantum Mechanics, posed by the already quoted paper by Einstein, Podolsky and Rosen [1]. In recent years the attention has been focused on EPR type experiments.

If we picks up a typical contemporary paper concerning EPR arguments, we are facing the following situation: the orthodox description is presented as a ‘non-realist’ one; philosophical realist positions are translated into a physical theory whose predictions are necessarily different, at least in some cases, from the ones of Quantum Mechanics; fatally, the ‘realist’ theory is disproved by experiments. In these papers, realist positions are characterized, among other conditions, by the statement ($SR$) that ‘it is possible to attribute a definite value to a physical quantity of a system before measurement’. This characterization is untenable because it is based on the assumption that ($SR$) is a philosophical assertion; as we shall see, it is a physical assertion and, therefore, it can be tested - at least in principle - by experiment (section 2.2.3).
2.2.1 Photon pairs correlated in polarization

Nowadays, these experiments are carried out by using photons pairs produced by parametric down conversion. However, we shall discuss first the ‘classical method’ based on pairs produced by atoms in a cascade process.

Let us consider a pair of photons produced by a single atom and flying away in opposite directions (for instance $\pm z$). When the photons are well apart, the photon $\nu_1$ flying, say, along $z$ is analyzed by polaroid $A$ while the other photon $\nu_2$ (flying along $-z$) is analyzed by polaroid $B$; behind the polaroids there is a photon detector. $A$ and $B$ make many measurements: we would like to know which is the correlation between the measurements of $A$ and $B$ as a function of the angle $\theta$ between their axis.

The photon pair is described by the state vector:

$$|\psi(\nu_1, \nu_2)> = \frac{1}{\sqrt{2}} (|R_1, R_2> + |L_1, L_2>)$$  \hspace{1cm} (3)

where $(|R>, |L>)$ are circular polarizations states. However, since a circularly polarized photon can be described as a combination of two linear polarizations, the above equation can be written in the form:

$$|\psi(\nu_1, \nu_2)> = \frac{1}{\sqrt{2}} (|x_1, x_2> + |y_1, y_2>)$$  \hspace{1cm} (4)

where $(|x>, |y>)$ are linear polarization state vectors.

Let us now suppose that the measurement by $A$ is made before the one made by $B$. If the photon pair is described by (3), then the probability that photon $\nu_1$ passes through $A$ is $(1/2)$; if $a$ is the direction of the axis of $A$, the photon pair, after the measurement made by $A$, is described by the state vector:

$$|\psi'(\nu_1, \nu_2> = |a, a>$$  \hspace{1cm} (5)

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3See, for instance, [7] and references therein.

4The first EPR type measurement with photons pairs produced by a cascade emission is due to Kocher and Commins [8]. The photons of the pairs produced by this type of source are not correlated in direction: therefore, the number of detectable correlated pairs is greatly reduced.

5Two filters, one on the $z$ path and the other on the $-z$ path, block the ‘wrong’ photons.

6Starting from Aspect’s experiment [3], the polaroids have been replaced by birefringent analyzers; however, this complication, suggested by Bell’s type inequalities known as BCHSH [10], can be avoided here since we are not interested in hidden variables theories.

7We are following the treatment by Aspect [11].
Therefore, if polaroid $B$ is oriented as polaroid $A$, photon $\nu_2$ passes through $B$; if, instead, $B$ is tilted by the angle $\theta$ with respect to $A$, photon $\nu_2$ will pass through $B$ with probability $\cos^2 \theta$ (Malus law). Then the probability that photon $\nu_1$ passes through $A$ and photon $\nu_2$ passes through $B$ is given by:

$$P(A, B) = \frac{1}{2} \cos^2 \theta$$

This equation can, of course, be derived directly from (4) by calculating the probability that photon $\nu_1$ passes through $A$ and photon $\nu_2$ passes through $B$ without considering the details of the experiment.

The usual interpretation is:

$(QM_1) A$ Before the measurement, the photons of each pair do not possess a definite value of the polarization.

$(QM_1) B$ Therefore, the photons pairs produced by the source are described by the state vector $|3\rangle$.

$(QM_1) C$ The probability for $\nu_1$ of passing through $A$ is $1/2$. If photon $\nu_1$ passes through $A$, then photon $\nu_1$ is (operationally) linearly polarized along the direction of the axis of $A$. Contemporaneously, photon $\nu_2$ assumes the same polarization.

$(QM_1) D$ If photon $\nu_1$ passes through $A$, then photon $\nu_2$ will pass through $B$ with probability $\cos^2 \theta$, where $\theta$ is the angle between the axis of the two polaroids (Malus law). Therefore, the probability that photon $\nu_1$ passes through $A$ and photon $\nu_2$ passes through $B$ is $(1/2) \cos^2 \theta$.

Let us now consider the following description obtained from the previous one by omitting the assumption $(QM_1) A$:

$(QM_0) A'$ The pair of photons produced by the source is described by the state vector $|3\rangle$.

$(QM_0) B'$ The probability for $\nu_1$ of passing through $A$ is $1/2$. If photon $\nu_1$ passes through $A$, then the photon pair is described by state vector $|5\rangle$; therefore, photon $\nu_2$ will pass through $B$ if it is oriented as $A$.

$(QM_0) C'$ If photon $\nu_1$ passes through $A$, then photon $\nu_2$ will pass through $B$ with probability $\cos^2 \theta$, where $\theta$ is the angle between the axis of the two polaroids (Malus law). Therefore, the probability that photon $\nu_1$ passes through $A$ and photon $\nu_2$ passes through $B$ is $(1/2) \cos^2 \theta$. 


The difference between the two descriptions is due to the presence - in the usual one - of the statement \((QM_1) A\): it entails, in sentence \((QM_1) C\), that a definite value of the polarization is given to the photon \(\nu_1\) by measurement; as a consequence, it is held that ‘contemporaneously, photon \(\nu_2\) assumes the same polarization’. This sentence incorporates an ‘instantaneous action at a distance’. It is claimed that special relativity is not violated since there is no information transport between \(A\) and \(B\): we can verify the correlations between the measurements made by \(A\) and those made by \(B\) only by bringing together their data. However, the process under challenge is not the reading by a human observer (who collects the data of \(A\) and \(B\)) but the purported physical process according to which the polarization measured by \(A\) on photon \(\nu_1\) is instantaneously ‘transmitted’ to photon \(\nu_2\): within the usual description, without this ‘transmission’, the human observer who collects the data from \(A\) and \(B\) would never see the observed correlations. As a matter of fact, given the unpopularity of the instantaneous action at a distance, it is spoken of non-local effects. Non-locality with its associated instantaneous action at a distance is a direct consequence of statement \((QM_1) A\) about the undefined value of polarization before measurement. If we drop this assumption, we switch to the labeled description that deals only with state vectors and experimental outputs and avoids non-local effects. However, in the labeled description, the choice of the starting state vector needs to be justified. This will be done in next section.

### 2.2.2 An operational definition of ‘correlated polarization’

The primed description of the Aspect experiment suggests the following operational definition of correlated polarization of the photon pairs:

> Put the two polaroids with their axis parallel. If, for every photon pair, photon \(\nu_1\) passes through \(A\) and photon \(\nu_2\) passes through \(B\), then the twin photons are said to be correlated in polarization.

This definition, based on state vector (3) (or, equivalently (4)), correlates an empirical property of the photon pairs with the state vector that describes them. In section 2.2.5 where all the so called ‘four Bell states’ are considered, it will be shown that to every ‘Bell state’ (state vector) corresponds a uniquely defined ‘correlated polarization’ of the twin photons. Therefore, a one-to-one correspondence exists between state vectors and ‘correlated polarization’ of the photon pairs. Since photon pairs described by different
Bell states have different ‘polarization correlations’, we must conclude that this ‘polarization correlation’ is a property of the photon pairs as they are produced by the source. In next section, the ‘polarization correlation’ of photon pairs produced by a cascade process will be further analyzed on the basis of two possible experiments.

2.2.3 Two possible experiments on the polarization of the twin photons beams of the Aspect experiment

The ‘polarization correlation’ operationally defined in previous section (and extended to all ‘Bell states’ in section 2.2.5) deserves a deeper understanding.

Our acquired knowledge says that conservation laws are valid in every single atomic event. Therefore, since the twin photons are emitted by two consecutive transitions from an initial $J = 0 \left(^1S_0\right)$ to an intermediate $J = 1$ state $\left(^1P_1\right)$ and to a final $J = 0$ state $\left(^1S_0\right)$, the twin photons are expected to be both right or left circularly polarized (angular momentum conservation). Therefore:

a) The beams flying along $\pm z$ should be made up by a (statistically) equal number of right and left circularly polarized photons: the beams should be unpolarized.

b) However, each photon should have a definite polarization: right or left. This point is usually neglected, probably owing to the idea that, before measurement, the twin photons cannot have a definite polarization since they are described by a pure state. This objection notwithstanding, let us follow this line of reasoning and see if it can deepen our understanding of the ‘correlated polarization’ property.

As suggested by classical optics, points a) and b) can be experimentally checked by the combined use a quarter wavelength plate and a polaroid. It is to be stressed that these measurements tell us which is the polarization of the photons before their entrance in the experimental apparatus (plate+polaroid).

a) Each photon of the beam should be either right or left polarized with probability $1/2$. If it is right, it will be, after the plate, linearly polarized along a direction $a$ tilted by an angle $\pi/4$ with
respect to the optical axis of the plate. Then, it will have a probability \( \cos^2 \theta \) of passing through a polaroid whose axis makes an angle \( \theta \) with \( \mathbf{a} \). Then the probability of passing the polaroid is \( (1/2) \cos^2 \theta \).

If the photon is left polarized, it will be, after the plate, linearly polarized along a direction \( \mathbf{b} \) tilted by an angle \( -\pi/4 \) with respect to the optical axis of the plate. Then, it will have a probability \( \sin^2 \theta \) of passing through a polaroid whose axis makes an angle \( \theta \) with \( \mathbf{a} \). Then the probability of passing the polaroid is \( (1/2) \sin^2 \theta \).

Since each photon is either right or left polarized, the probability of passing through the polaroid is \( (1/2) \cos^2 \theta + (1/2) \sin^2 \theta = 1/2 \), independent of \( \theta \). Therefore, the intensity of the light beam does not change by rotating the polaroid.

b) A quarter wavelength plate and a polaroid (with its axis tilted by \( \pi/4 \) with respect to the optical axis of the plate in order to detect, say, right circularly polarized photons) are inserted into the photons’ \( \pm z \) paths (with the blocking filters). We should observe that when a photon is detected along \( z \) a photon is detected also along \( -z \): then, we must conclude that the twin photons were right circularly polarized before their entrance into the measuring apparatus (plate plus polaroid). By rotating both polaroids by \( \pi/2 \), the photomultipliers will detect in coincidence only left circularly polarized photons. Finally, by putting the two polaroids in such a configuration that the two measuring devices (plate + polaroid + photon detector) detect, respectively, right (along \( z \)) or left (along \( -z \)) circularly polarized photons, we shall have a ‘click’ only along \( z \) or \( -z \) for every photons pair.

### 2.2.4 A third, possible description

Let us suppose that the basic idea leading to the experiment proposed in b) is correct: the twin photons are both right or left polarized. Then, using the

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8In literature, there are two different definition of right/left polarization: which is right for one, is left for the other; and vice versa. Of course, our argumentation is valid whichever definition is chosen.

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definition of ‘correlated polarization’ of section 2.2.2, we can build up the following description of the experiment:

(QM_0) A'' The polarization of the photons of a pair produced by the source is correlated.

(QM_0) B'' Each photon of the pair does possess a definite value of the polarization: it is either right or left circular.

(QM_0) C'' Since photon \( \nu_1 \) is right or left circularly polarized, it has probability \( 1/2 \) of passing through polaroid \( A \).

(QM_0) D'' If photon \( \nu_1 \) passes through \( A \), since the polarization of the photon pair is correlated, then photon \( \nu_2 \) passes through \( B \) if its orientation is the same as that of \( A \); otherwise, it will pass through \( B \) with probability \( \cos^2 \theta \), where \( \theta \) is the angle between the axis of the two polaroids (Malus law). Therefore, the probability that photon \( \nu_1 \) passes through \( A \) and photon \( \nu_2 \) passes through \( B \) is \( (1/2) \cos^2 \theta \).

This description is based on two features that are usually considered as incompatible: pure states and definite values of a physical quantity before measurement. However, the fact that it leads to the correct predictions suggests that this incompatibility may not be there: only the experimental test suggested above could clear this point.

2.2.5 Extension to photons pairs produced by parametric down conversion

Parametric down conversion allows to produce all of the so called ‘four Bell states’:

\[ \psi^\pm = (1/\sqrt{2})(|x_1,y_2> \pm |y_1,x_2>); \quad \phi^\pm = (1/\sqrt{2})(|x_1,x_2> \pm |y_1,y_2>); \]

where \( x \) and \( y \) are two perpendicular linear polarization states. A general definition of ‘correlated polarization’, applicable to each of the four Bell states, is as follows:

Put the two measuring polaroids \( A \) and \( B \) in such a configuration (relative orientations of their axis) that, for every photon pair, if a photon of the pair passes through \( A \), then the twin photon passes through \( B \). If this is possible, then the photons pairs are said to be correlated in polarization.
The relative orientation of the two polaroids depends on which of the four ‘Bell states’ is considered: parallel for the $\phi^+$ state; perpendicular for the $\psi^+$ state; $\theta_B = -\theta_A$ for the $\phi^-$ state; $\theta_B = -\theta_A + \pi/2$ for the $\psi^-$ state. Using the above general definition of ‘correlated polarization’, it is possible to set up a description analogous to the doubled primed one discussed in section 2.2.2 for each of the four Bell states.

Example. In the case of the $\phi^-$ state, the double primed description goes as follows: i) the polarization of the photons of a pair is correlated; ii) before any measurement, each photon of the pair does possess a definite value of the polarization: it is either $x$ or $y$ linear polarization; iii) since photon $\nu_1$ is either $x$ or $y$ linearly polarized, it has probability $1/2$ of passing through polaroid $A$ oriented along $\theta_A$ (arbitrarily chosen); iv) if photon $\nu_1$ passes through $A$, since the polarization of the photons of the pair is correlated, then photon $\nu_2$ passes through $B$ if it is oriented along $\theta_B = -\theta_A$; otherwise, it will pass through $B$ with probability $\cos^2(\theta_A + \theta_B)$ (Malus law); v) therefore, the probability that photon $\nu_1$ passes through $A$ and photon $\nu_2$ passes through $B$ is given by $(1/2)\cos^2(\theta_A + \theta_B)$.

3 Causality

The causality principle has been frequently challenged after the formulation of Quantum Mechanics. It is claimed that, while probabilistic theories of classical physics reflects our ignorance about phenomena, the probabilistic nature of Quantum Mechanics reflects the indeterministic nature of quantum phenomena.

The attribution of a general feature of a theory (in this case its probabilistic nature) to the World constitutes a strong realist assertion about how things behave in the World: then, we are called to carefully evaluate its plausibility. However, the main point is that the ‘causality principle’, understood as a methodological commitment to the searching for causes, has been one of the propulsive forces of scientific knowledge: a discipline that, on the basis of hardly conclusive evidence, is really abandoning this commitment, is doomed to drain its vital sources.
4 Conclusions

The debate about EPR issues has been characterized by the confrontation of a ‘realistic stand’ - originally attributed to Einstein - with a ‘quantum mechanical’ one. This confrontation has been played, though not uniquely, about the question ‘Q’: “Can we attribute a definite value to a physical quantity before measurement? Or is the process of measurement that attributes this definite value to the quantity under measurement?” The answer given in this paper is:

A) Question ‘Q’ is a physical question, not a philosophical one. As such, it can be decided by experiment (section 2.2.3).

B) In the case of EPR experiments with twin photons pairs the state vectors describing the photon pairs are chosen because they describe the correct correlation between the polarizations of the twin photons and not on the basis of the defined/undefined value of the polarization before measurement (sections 2.2.2 and 2.2.5).

C) The non-locality effects appearing in the usual interpretation of these EPR experiments are due to the hypothesis (explicit or implicit) that ‘only the process of measurement attributes a definite value to the quantity under measurement’ (section 2.2.1). If we drop this hypothesis, and this can be done without changing the predictions of the theory, non-locality effects disappear (sections 2.2.1 and 2.2.4).

The discussion about the epistemological status of Quantum Mechanics has been characterized, since its beginnings, by the confrontation of different philosophical positions. This discussion has increasingly spread over and outside the scientific community and has produced an impressive huge number of papers and books: it is hard avoiding the uncomfortable feeling that this discussion has drained much more intellectual resources than deserved.

Starting from Bell’s paper [2], a bizarre game has been played: to build up theories labeled as realist; and to realize increasingly sophisticated experiments in order to disprove them. If we like, we can go on playing the game; however, since the postulates of a theory cannot be logically deduced

\[ \text{[Footnote]} \]

However, these sophisticated experiments have enlarged our knowledge on how to produce and manipulate correlated photons pairs.
from a philosophical position, we must be aware that *experiments disprove sometimes a theory but never a philosophy.*

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