On realism and quantum mechanics

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Summary. — 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 ones 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 confutation 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.

PACS `03.65.-w` – Quantum mechanics.
PACS `03.65.Ud` – Entanglement and quantum nonlocality (*e.g.*, EPR paradox, Bell's inequalities, GHZ states, etc.).

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 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 ones 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

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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-state system S described by the state vector

$$(1) \qquad |\psi\rangle = \frac{1}{\sqrt{2}} \left(|\psi_1\rangle + |\psi_2\rangle \right),$$

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 $|\psi_1\rangle$ is a_1 and, correspondingly, a_2 for $|\psi_2\rangle$.

Here are two possible interpretations of eq. (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 (1). 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 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 (1). ($M2$) 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 θ from that of the first polaroid, quantum mechanics predicts that each photon has probability $\cos^2 \theta$ of passing through the second polaroid[1]. Quantum mechanics does so by describing the incoming photon by a "superposition" of linear polarizations along two perpendicular directions x', y'[2]:

$$(2) \qquad\qquad |x\rangle = |x'\rangle \cos\theta + |y'\rangle \sin\theta \, .$$

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 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 eq. (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 eq. (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".

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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.

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 (subsubsect. $2\dot{}2.3$).

$2\dot{}2.1$. Photon pairs correlated in polarization. Nowadays, these experiments are carried out by using photons pairs produced by parametric down conversion[3]. However, we shall discuss first the "classical method" based on pairs produced by atoms in a cascade process [8][4].

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 ν_1 flying, say, along z is analyzed by polaroid A while the other photon ν_2 (flying along $-z$) is analyzed by polaroid B; behind the polaroids there is a photon detector[5][6]. 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 θ between their axis.

The photon pair is described by the state vector

$$(3) \qquad |\psi(\nu_1, \nu_2)\rangle = \frac{1}{\sqrt{2}} \left(|R_1, R_2\rangle + |L_1, L_2\rangle \right),$$

where $(|R\rangle, |L\rangle)$ 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

$$(4) \qquad |\psi(\nu_1, \nu_2)\rangle = \frac{1}{\sqrt{2}} \left(|x_1, x_2\rangle + |y_1, y_2\rangle \right),$$

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

Let us now suppose that the measurement by A is made before the one made by B[7]. If the photon pair is described by (3), then the probability that photon ν_1 passes through A is $(1/2)$; if $\mathbf{a}$ is the direction of the axis of A, the photon pair, after the measurement made by A, is described by the state vector

$$(5) \qquad |\psi'(\nu_1, \nu_2)\rangle = |\mathbf{a}, \mathbf{a}\rangle.$$

Therefore, if polaroid B is oriented as polaroid A, photon ν_2 passes through B; if, instead, B is tilted by the angle θ with respect to A, photon ν_2 will pass through B with probability $\cos^2 \theta$ (Malus law). Then the probability that photon ν_1 passes through A and photon ν_2 passes through B is given by

$$(6) \qquad P(A, B) = \frac{1}{2} \cos^2 \theta.$$

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[3] See, for instance, [7] and references therein.
[4] The first *EPR*-type measurement with photons pairs produced by a cascade emission is due to Kocher and Commins [9]. 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.
[5] Two filters, one on the z path and the other on the $-z$ path, block the "wrong" photons.
[6] Starting 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.
[7] We are following the treatment by Aspect [11].

This equation can, of course, be derived directly from (4) by calculating the probability that photon ν_1 passes through A and photon ν_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).

$(QM_1)\,C$ The probability for ν_1 of passing through A is 1/2. If photon ν_1 passes through A, then photon ν_1 is (operationally) linearly polarized along the direction of the axis of A. Contemporaneously, photon ν_2 *assumes* the same polarization.

$(QM_1)\,D$ If photon ν_1 passes through A, then photon ν_2 will pass through B with probability $\cos^2\theta$, where θ is the angle between the axis of the two polaroids (Malus law). Therefore, the probability that photon ν_1 passes through A and photon ν_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).

$(QM_0)\,B'$ The probability for ν_1 of passing through A is 1/2. If photon ν_1 passes through A, then the photon pair *is described* by state vector (5); therefore, photon ν_2 will pass through B if it is oriented as A.

$(QM_0)\,C'$ If photon ν_1 passes through A, then photon ν_2 will pass through B with probability $\cos^2\theta$, where θ is the angle between the axis of the two polaroids (Malus law). Therefore, the probability that photon ν_1 passes through A and photon ν_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 ν_1 by measurement; as a consequence, it is held that "contemporaneously, photon ν_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 ν_1 is instantaneously "transmitted" to photon ν_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 subsubsection.

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 ν_1 passes through A *and* photon ν_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 subsubsect. **2**˙2.5, where all the so-called "four Bell states" are considered, it will be shown that to every "Bell state" (state vector) there 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 subsubsection, 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 subsubsection (and extended to all "Bell states" in subsubsect. **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 $J = 0$ ($^1S_0$) to an intermediate $J = 1$ state ($^1P_1$) and to a final $J = 0$ state ($^1S_0$), 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 of 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([8]). Then, it will have a probability $\cos^2 \theta$ of passing through a

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([8]) In the literature, there are two different definitions 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.

polaroid whose axis makes an angle θ 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 θ 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 θ. 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.

$\mathbf{2}\text{\textperiodcentered}2.4.$ 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 definition of "correlated polarization" of subsubsect. $\mathbf{2}\text{\textperiodcentered}2.2$, 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 ν_1 is right or left circularly polarized, it has probability $1/2$ of passing through polaroid A.

$(QM_0)\,D''$ If photon ν_1 passes through A, *since the polarization of the photon pair is correlated*, then photon ν_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 θ is the angle between the axis of the two polaroids (Malus law). Therefore, the probability that photon ν_1 passes through A and photon ν_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":

$$\psi^{\pm} = (1/\sqrt{2})(|x_1, y_2\rangle \pm |y_1, x_2\rangle); \qquad \phi^{\pm} = (1/\sqrt{2})(|x_1, x_2\rangle \pm |y_1, y_2\rangle),$$

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 ϕ^+ state; perpendicular for the ψ^+ state; $\theta_B = -\theta_A$ for the ϕ^- state; $\theta_B = -\theta_A + \pi/2$ for the ψ^- 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 subsubsect. **2**˙2.2 for each of the four Bell states.

> Example. In the case of the ϕ^- 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 ν_1 is either x or y linearly polarized, it has probability $1/2$ of passing through polaroid A oriented along θ_A (arbitrarily chosen); iv) if photon ν_1 passes through A, since the polarization of the photons of the pair is correlated, then photon ν_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 ν_1 passes through A and photon ν_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 (subsubsect. **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 (subsubsects. **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" (subsubsect. **2**˙2.1). If we drop this hypothesis, and this can be done without changing the predictions of the theory, non-locality effects disappear (sects. **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[9]. If we like, we can go on playing the game; however, since the postulates of a theory cannot be logically deduced from a philosophical position, we must be aware that *experiments disprove sometimes a theory but never a philosophy.*

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