Realistic Aspects in the Standard Interpretation of Quantum Mechanics*

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ABSTRACT

The belief that quantum mechanics (QM) does not admit a realistic interpretation is widespread. According to some scholars concerned with the foundations of QM all existing interpretations of this theory (except for the statistical interpretation) presuppose instead a form of realism which consists in assuming that QM deals with individual objects and their properties. We uphold in the present paper that the arguments supporting the contextuality and the nonlocality of QM are a significant clue to the implicit adoption of stronger forms of realism (*realism of theoretical entities* and *realism of theories*). If these kinds of realism are substituted by a simpler and more intuitive *semantic realism* one can contrive a noncontextual and local interpretation of the formalism of QM (*SR interpretation*). Moreover one can provide a model for such an interpretation (*ESR model*) in which *local realism* and QM do not conflict and some fundamental problems of the standard interpretation of QM are avoided.

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* The present paper was originally conceived as an English translation of a paper by C. Garola, published in Italian in *Giornale di Fisica*, Vol. L, Suppl. 1, 2009. During the translation process the paper has been entirely revised with the contribution of S. Sozzo and a final section has been added.

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I

In a recent paper T. Norsen (2007) listed four basic forms of realism, with the aim of comparing them with the notion of realism implied by the term *local realism*, widely used in the physical literature concerning Bell's theorem and the problems connected with it. Apart from the conclusions, from some aspects disputable[1], Norsen's paper is interesting because it stimulates new reflections on the different forms of realism introduced in physics and on their relations with the notions of realism that one usually meets in the philosophical literature. We briefly discuss some aspects of these problems in the present paper by referring to one of the fundamental theories of modern physics, namely quantum mechanics (QM). We intend to show that the prevailing physicists' attitude presupposes compelling philosophical choices, notwithstanding the claimed "antimetaphysical" character of the orthodox interpretation of the formal apparatus of QM[2], and that these choices raise some nontrivial problems.

II

The belief that QM does not admit a realistic interpretation is commonly accepted among physicists, but the sense of this conviction is ambiguous if one does not specify the form of realism to which one is referring. For example, according to Busch et al. all existing interpretations of QM, but the *statistical interpretation*, are realistic in the sense that they all agree that «quantum mechanics deals with individual objects and their properties» (Busch et al. 1991, p. 5). Nevertheless such a form of realism is very weak, even though its implications are not trivial. One can then wonder whether the standard interpretation of QM presupposes more compelling forms of realism, and

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[1] According to Norsen the notion at issue does not fit in with any previous definition of realism and should be avoided. But the term *local realism* has a precise meaning in the physical literature and is widely used, hence we think that it should be preserved, even though it denotes a kind of realism that does not fall within standard philosophical classifications.

[2] Such an orthodox interpretation is often called *standard*, or *Copenhagen*, *interpretation* of QM. This terminology is incorrect, both because the interpretation of a physical theory should be considered as a part of the theory itself (see §.II), and because there were different positions in the Copenhagen school about the interpretation of the formalism of the new theory (Tassani 2004). For the sake of brevity, however, we adopt the current terminology in the following.

whether alternative interpretations exist that imply further different forms. An exhaustive answer to this question would require a complex preliminary analysis of the linguistic structure of scientific theories that cannot be undertaken here. Therefore we limit ourselves to present an outline of the epistemological perspective that we adopt in this paper (which is mainly based on the *received* viewpoint.[3]

According to our perspective, any scientific (e.g., physical) theory $\mathcal{T}$ is stated by using a fragment of a natural language, enriched by conventional and technical symbols (the *metalanguage* of $\mathcal{T}$). This fragment contains in particular a *theoretical language* L_T and an *observational* (or *pre-theoretical*) *language* L_O. The former contains terms denoting theoretical entities and their relations (in particular, L_T contains the mathematical apparatus of $\mathcal{T}$), and constitutes a formal structure. The latter is interpreted on objects and events of the physical (observable) world by means of *assignment rules* which provide an interpretation of L_O, usually in terms of *operational definitions*, which constitutes the basis for any further interpretation, in particular of L_T. L_O is thus provided with semantics and a notion of truth. Moreover a mapping exists of L_O onto a sublanguage L_{TO} of L_T, which implies that there are *correspondence rules* (or *bridge principles*) that inversely relate L_{TO} with L_O, supplying an empirical interpretation of L_T (which is necessarily *partial*, for $L_{TO} \subset L_T$, and *indirect*, for it concerns only derived and not primitive terms of L_T). The following remarks are then relevant.

(i) The mapping of L_O on L_{TO} generally is not bijective. Hence different terms of L_O may exist which are mapped into the same term of L_{TO}.

(ii) The laws of $\mathcal{T}$ that are expressed by means of the mathematical formalism of L_T must be considered *theoretical laws*. Some of them are expressed by means of the sublanguage L_{TO} and allow one to state, via correspondence rules, *empirical laws* that are expressed by means of L_O and can be experimentally checked, hence confirmed or falsified.

(iii) The mathematical apparatus of $\mathcal{T}$ is generally provided with a *model* $\mathcal{M}$, that is, it is mapped on another mathematical (usually geometrical and intuitive) structure which provides a *complete* interpretation of L_T. It should be stressed, however, that such an interpretation does not map L_T on a physical domain unless the theoretical entities of the

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[3] See Braithwaite 1953 and Hempel 1965.

model are assumed to represent entities that actually exist in the physical world.

III

Bearing in mind the scheme proposed in §.II one can identify various kinds of realism in the interpretations of physical theories. In particular, there exists a widespread tendency to consider the theoretical entities in $\mathcal{T}$ (denoted by terms in L_T) as constituents of a reality existing beyond mere physical phenomenology and sensory data (*realism of theoretical entities*, or, briefly, *RTE*[4]). This tendency can be implemented in two different ways.

(i) By implicitly assigning to intuition the capability to grasp parts of reality, hence by assuming the entities of the model $\mathcal{M}$ of $\mathcal{T}$ as real.

(ii) By directly considering the mathematical entities in L_T as faithful representations of some reality underlying the phenomena of the physical world, hence identifying them with this reality.

Position (i) often occurs in classical physics. Newton's absolute space (which opposes, because of deep ideological reasons, the relational notion of space upheld by Leibniz), motions and trajectories of classical mechanics (whenever mass points and forces are interpreted as parts of reality), waves of classical electromagnetism (whenever also electric and magnetic fields are interpreted as parts of reality) are examples of it.[5]

Position (ii) is instead more frequent in modern physics whenever the difficulties in working out consistent geometric and intuitive models of nonclassical theories, as QM, lead one to directly assume the theoretical

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[4] RTE is also called *scientific realism* in the literature. We prefer the acronym RTE here to stress the difference between the notion of scientific realism and the notion of *semantic realism* that is introduced in the following, because these notions lead to antithetical conclusions (see §.VII). We note that, according to some authors (Alai 2009), scientific realism can be *metaphysical* (if independence of the theoretical entities denoted by terms in L_T from perception and thought is assumed) or *empirical* (if reality only of the theoretical entities denoted by terms in L_T is assumed). This distinction, however, is problematical, and our arguments in this paper are independent of it.

[5] It is interesting to note that also the old debate on the nature of the physical entities described by QM, that is, whether they were waves or particles, was possible and meaningful only in a perspective in which waves and particles were considered as alternative parts of reality.

entities in L_T as real (we discuss in details some examples of this position in §.IV).

It is well known that RTE may have a positive role in the development of a scientific theory, stabilizing its theoretical content and stimulating research within the theory. But it may also constitute a serious hindrance to the research progress because the empirical relations described in L_O do not determine univocally the theoretical apparatus, hence L_T. Therefore, different theoretical apparatuses generally exist which are equivalent with respect to the description of a given empirical domain, hence the construction of L_T requires the adoption of nonempirical additional criteria (simplicity, intuitiveness, etc.). These criteria, together with their interpretation, change with the cultural context, and an enrichment of the overall knowledge may require their modification, which in its turn implies a modification of L_T. Moreover, since L_T is not univocally determined, complex procedures of empirical control are defined for each theory $\mathcal{T}$, and a possible falsification may impose a modification of L_T. In both cases a conflictual situation occurs, since significant variations of L_T demand constructing a new picture of reality and renouncing previously well-grounded parts of reality (which is psychologically and conceptually difficult).

It should be noted, however, that nowadays physicists generally assert their indifference (or hostility) towards any ontological commitment. Hence our foregoing statement about the existence of forms of RTE in modern physics should regard only a minority of scholars. But let us observe that recently there has been a large increase in the theoretical apparatuses of some areas of physics (e.g., string theory[6]), without a comparable rise in the empirical data, which has strengthened the propensity to attribute an absolute role to the mathematical formalism. Therefore many physicists implicitly assume that only what can be described by the formalism of the theory $\mathcal{T}$ they are dealing with has a physical meaning, thus considering the formalism as exhaustive of the physical reality to which $\mathcal{T}$ applies. This attitude sets aside the distinction between L_O and L_T and introduces a form of RTE of the kind described in (ii), whatever the claimed epistemological attitude may be.

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[6] See Smolin 2005.

IV

We have seen in §.II that the mapping of L_O into L_{TO} is generally not bijective. Indeed, it may occur that terms in L_O denoting different observational entities correspond to the same theoretical term in L_{TO}. From the point of view of the mere mathematical formalism the observational entities at issue are then equivalent, but they are not equivalent from the point of view of the predictions of the theory following from the empirical interpretation (see §.II). Nevertheless the identity of the mathematical representations may induce, or facilitate, the identification of such observational entities, which may lead to physically disputable consequences.

Because of the relevance of the above argument we illustrate it by means of examples, referring to QM, which is the theory that we intend to consider in the present paper.

Example 1. A *state* S of a physical system Σ is operationally defined as a class of physically equivalent *preparing devices*. Each preparing device, when constructed and activated, produces an individual example of Σ or, briefly, a *physical object*. A *physical property* E of Σ is operationally defined as a class of physically equivalent *registering devices*. Each registering device, when applied to a physical object x in a state S (that is, a physical object prepared by means of a preparing device belonging to S) produces one of two possible answers (for example, *yes/no*). States and properties have therefore quite different operational definitions. Nevertheless, a subset of states and a subset of properties exist which can be put in a one-to-one correspondence: namely, the subset of *pure states* and the subset of *atomic properties* in the lattice of all properties of Σ.[7] Moreover, a pure state S and the atomic property E_S corresponding to it (usually called the *support* of S) are represented by the same mathematical entity (a one-dimensional projection operator of the form $|\psi\rangle\langle\psi|$, with $|\psi\rangle$ unit vector of the Hilbert space $\mathcal{H}$ associated with Σ) in QM. This representation therefore suggests one to identify S and E_S (that are obviously terms of L_O), especially if a role is attributed to the mathematical apparatus which goes beyond the role of mere formal representation (conversely, the identification itself may constitute a clue of a possible

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[7] For the sake of brevity, we do not enter into technical details defining explicitly these notions, see, e.g., Beltrametti and Cassinelli 1981.

epistemological position of this kind, e.g., RTE). By analyzing the literature on this argument one then finds that the identification between S and E_S is in fact a basic element in at least a conceptually relevant semi-axiomatic approach to QM (Piron 1976). Furthermore, this identification is sometimes implicitly accepted in the current literature (Bouwmeester et al. 1997).

On the other hand, missing the distinction between pure states and their support can lead to misunderstandings. Indeed, a physical object in a pure state S possesses the support E_S of S with certainty, but physical objects may exist which display the property E_S in a measurement without being prepared in the state S. From a semantic point of view one can say that the *extensions* of S and E_S do not necessarily coincide, while the identification of S and E_S can lead one to identify them, as it occurs in the example that follows. More generally, representing S and E_S by means of the same mathematical term in L_T implies that the semantic differences between S and E_S are not preserved in the syntactic apparatus of L_T, which constitutes a serious limit of the technical language of QM.

Example 2. Many manuals and popular books on QM introduce the reader to the surprising features of QM by discussing the well known two-slit experiment, or a modern variant of it (Mach-Zehnder interference experiment[8]). This experiment can be synthetically described as follows.

A monochromatic beam of light hits a screen with two close slits, say 1 and 2, and light is then collected on a faraway second screen. Whenever both slits are open the light distribution on the second screen is not the superposition of the two distributions that can be obtained by closing either slit 1 or slit 2. Rather, an interference pattern appears which suggests that the beam should be described as a wave. On the other hand the same experiment produces isolated spots on the second screen if it is performed with a low intensity beam, which suggests that the beam should be described as a bunch of particles. According to current literature these contradictory results can be explained only accepting a particle model for the beam but avoiding attributing to the particles all the features that they should have according to classical physics. The reasoning leading to this conclusion proceeds *ab absurdo* and can be schematized as follows.

(i) A seemingly obvious premiss of *objectivity* is stated:

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[8] See, e.g., Albert 1992, etc.

(O) *Each particle possesses the* property E_1 *of passing through slit 1 or the property* E_2 *of passing through slit 2.*

(ii) Because of O one can consider all particles that possess the property E_1 (E_2): these should produce the same distribution on the final screen that is produced by particles passing through slit 1 (2) when slit 2 (1) is closed.

(iii) It follows that the overall distribution should be the superposition of the two distributions obtained by closing either slit 1 or slit 2.

(iv) Experimental data do not confirm conclusion (iii).

(v) Because of (iv) premiss (O) is falsified.

(vi) Hence, for every particle, the property of passing through a given slit cannot *a priori* be considered as possessed or not possessed by the particle, as it occurs in classical physics. A property of this kind is a *nonobjective*, or *potential*, property that may become *actual* only if a measurement is performed determining which option occurs. Therefore the quantum notion of particle differs in a fundamental way from the classical notion.

The argument expounded above is widespread and commonly accepted. It is therefore important to observe that statement (ii) does not follow from statement (i). Rather, statement (ii) introduces an implicit *additional* assumption, which can be made explicit as follows.

(A) *A particle possessing the* property E_1 *(*E_2*) whenever slits 1 and 2 are both open is physically equivalent (at least with respect to the distribution on the second screen) to a particle* prepared *by leaving slit 1 (2) open and slit 2 (1) closed.*

The explicit statement of assumption (A) makes it evident that statement (ii) postulates a physical equivalence between properties and preparations, hence states (which implies, in particular, that E_1 and E_2 are mutually exclusive). As long as the operational definitions of states and properties are not explicitly given, assumption (A) seems intuitively obvious because one implicitly assumes an elementary model according to which particles move along straight trajectories. But if one refers to the operational definitions introduced in

Example 1 and avoids naïve models, assumption (A) is questionable[9], and the experimental falsification of conclusion (iii) does not necessarily falsify (O), because it could instead show that (A) does not hold. Nevertheless, representing pure states and their supports by means of the same mathematical entities provides a natural, though improper, backup to assumption (A), especially if one accepts, more or less explicitly, RTE in the version (ii) of §.III (it is probably because of this backup that the critics to the two-slit argument, which is implicit in the reasoning above, has never been propounded by other authors[10]).

Example 3. Besides pure states, *mixed states*, or *proper mixtures*, are usually introduced in QM. A proper mixture M can be operationally defined as a set of pure states in which each pure state S in associated with a weight p_S, interpreted as the epistemic probability (which expresses a subjective lack of knowledge about the physical situation) that the system be actually prepared in the pure state S. Hence the term "M" belongs to L_O. Moreover, the proper mixture M is represented by a density operator ρ on $\mathcal{H}$ in QM (the technical features of a density operator are not relevant for our purposes). Hence the term "ρ" belongs to L_{TO}. Then, several problems arise because of such definition and representation.

(i) A given density operator corresponds to some different operational definitions that are equivalent as far as probabilities of physical properties are concerned, hence the corresponding mixtures are identified in QM. But this identification overlooks the fact that different operational definitions are not equivalent at an individual level because the possible pure states of the physical object that is considered are different when the operational definitions are different.

(ii) It follows from (i) that the knowledge of a density operator ρ is not sufficient to pick out a single operational definition, which implies that the coefficients in the decomposition of ρ into pure states cannot generally be interpreted as epistemic probabilities (Beltrametti and Cassinelli 1981).

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[9] For instance, one cannot *a priori* exclude that the particle possesses both the property of passing through slit 1 and the property of passing through slit 2 whenever both slits are open. Indeed, these properties could be possessed by the same particle at different times (a straight trajectory of the particle would of course be excluded in this case).

[10] See Garola 2000.

Example 4. Also *improper mixtures* are introduced in QM (d'Espagnat 1976). An improper mixture N is operationally defined in a complex way, which is equivalent to assigning a set of pure states in which each pure state S is associated with a weight p_S, as in the case of a proper mixture, hence the term "N" belongs to L_O. In this case, however, p_S can never be interpreted as an epistemic probability. This notwithstanding also the improper mixture N is represented by a density operator ρ on $\mathcal{H}$ in QM. It follows that the same term in L_{TO} can represent both a proper and an improper mixture. This identity of representations may lead one to disregard the distinction between the two kinds of mixtures, reaching the doubtful conclusion that the problems of the quantum theory of measurement can be solved within the standard interpretation of QM (Garola and Sozzo 2007, Genovese 2005, Schlosshauer 2004).

Examples 1-4 illustrate the theses expounded at the beginning of this section. Summarizing, they show that the technical language of QM has serious limits because the mathematical representations do not distinguish some different physical entities, hence the language L_T of QM does not adequately express the semantic differences existing in the language L_O on which L_T is interpreted (L_T should therefore be suitably extended: attempts in this direction have been forwarded in particular by the Brussels school[11], but they are generally ignored by physicists involved in the foundations of QM). These expressive limits of L_T may suggest or support the improper identification of different observational terms having the same mathematical representations. It is now important to observe that such an identification naturally follows if one accepts a form of RTE of the kind discussed in §.III, (ii). Therefore, overlooking the important distinctions illustrated in the previous examples constitutes in our opinion a significant clue to an implicit adoption of RTE.

V

The conclusions expounded at the end of §.IV would probably be considered inessential by most physicists, who usually rely on the mathematical formalism and are scarcely sensitive to epistemological analysis of the kind carried out in

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[11] See Aerts 1999.

§.IV. Moreover many scholars would claim that our invalidation of the two-slit argument on the basis of the distinction between states and properties is unimportant because, for every physical object in a given state, the existence of nonobjective properties can be asserted on the basis of more rigorous arguments, i.e., the Bell theorem (Bell 1964) and the Bell-Kochen-Specker, or Bell-KS, theorem (Bell 1966, Kochen and Specker 1967) that are usually maintained to prove the *nonlocality* and *contextuality*, respectively, of QM (we recall that these features of QM play a relevant role in quantum information and quantum computation). It is therefore relevant to our aims to observe that the proofs of these theorems depend on some epistemological assumptions that are unanimously accepted without being explicitly recognized, and that these assumptions can be questioned when looked into more deeply. Since this statement is compelling, we resume its proof in §.VI, limiting ourselves to the Bell-KS theorem for the sake of brevity, and introduce here some preliminary notions that are needed to this end.

First of all, let us observe that, bearing in mind the framework introduced in §.II, we can single out two disjoint subclasses in the class of all theoretical laws of classical and quantum physics.

(i) The class of all laws stated by means of $L_T \setminus L_{TO}$, consisting of mathematical expressions that have not a direct physical interpretation on the domain of physical facts.

(ii) The class of all laws stated by means of L_{TO}, consisting of mathematical expressions, generally deduced from the laws of the former class, which allow one to state in L_O, via correspondence rules, empirical laws that can be confirmed or falsified (by abuse of language, we briefly call *empirical laws* also the laws belonging to this class in the following).

This remark allows one to point out a fundamental distinction between classical and quantum theories. In classical theories there is no theoretical limit to the possibility of confirming or falsifying an empirical law. In QM instead, this possibility is restricted because *incompatible observables* occur in QM whose values can be neither measured nor predicted simultaneously. Indeed, incompatibility entails that physical situations may exist in which an empirical law can be, in principle, neither confirmed nor falsified. A situation of this kind occurs, e.g., whenever a physical object (individual example of a physical system, see §.IV) is known to possess a property E, and the empirical law that one is considering establishes a relation between two further compatible properties that are not compatible with E. Then, two different positions can be adopted about the truth value of a sentence α of L_{TO} expressing an empirical physical law (Garola and Pykacz 2004, Garola and Solombrino 1996a, Garola and Solombrino 1996b).

Metatheoretical classical principle (*MCP*). α is *true* in every physical situation that can be devised, even if this situation is such that QM does not allow one to check the empirical law expressed by α.

Metatheoretical generalized principle (*MGP*). α is *true* in every physical situation in which the law can be checked (*epistemically accessible physical situation*), while it may be *true* as well as *false* in physical situations in which QM does not allow one to check the physical law expressed by α.

Accepting MCP implies maintaining that empirical physical laws express relations on the set of theoretical entities that hold at a deeper level of reality, beyond the level in which empirical confirmation is possible. Accepting MGP implies instead a weaker *truth mode* of empirical physical laws, is consistent with the "antimetaphysical" attitude underlying QM and avoids any form of RTE.

VI

Let us come now to the Bell-KS theorem. As we have anticipated in §.V, this theorem is maintained to provide a rigorous support to the conclusions traditionally attained by means of the two-slit experiment (§.IV, Example 2) stating that, if one accepts the assumption that QM deals with physical objects and their properties, then for every physical object in a given state there are properties which depend on the set of measurements that are performed on the object (*contextual*, or *nonobjective*, or *potential*, properties). Therefore these properties cannot be considered as possessed or not possessed by the object independently of the experimenter's choices.

All proofs of the Bell-KS theorem assume (sometimes, implicitly) the following condition (Bell 1966, Kochen and Specker 1967; see also Mermin 1993).

KS. Let A, B, ... be compatible observables and let

$$f(A, B, \ldots)=0 \qquad (1)$$

express an empirical quantum law. Then, whenever measurements of A, B, ... are performed obtaining the outcomes a, b, ..., respectively, the following equation

$$f(a, b, ...)=0 \tag{2}$$

holds.

Condition KS is needed if one wants to get predictions from empirical laws, hence it must be accepted for physical reasons. All proofs then proceed *ab absurdo.* They consider several empirical quantum laws,

$$\begin{cases} f(A, B, \ldots) = 0 \\ g(A', B', \ldots) = 0 \\ \quad \ldots\ldots\ldots\ldots \end{cases} \tag{3}$$

assume that the values a, b,...; a′, b′,...; ... of the observables A, B,...; A′, B′,...; ... respectively, are defined independently of any measurement procedure for any physical object x, apply the KS condition *repeatedly*, which implies that f(a, b,...)=0, g(a′, b′,...)=0, ... must hold simultaneously, and finally show that a contradiction occurs. A seemingly unavoidable conclusion is that the values a, b,...; a′, b′,...; ... are not defined independently of the set of measurements that are performed (contextuality), hence cannot be considered as preexisting to the measurements.

The proofs schematized above are mathematically correct. However, a careful analysis shows that their premises follow from the adoption, implicit but essential, of the epistemological position MCP introduced in §.V. Indeed, we have seen that each proof requires a repeated application of the KS condition. But direct inspection shows that in every proof there are observables in a law (say, f(A, B,...)=0) that are not compatible with some observables in another law (say, g(A′, B′,...)=0). Whenever the values a, b,...; a′, b′,... are simultaneously attributed to the physical object x, a nonaccessible physical situation is devised in which only one (at choice) of the empirical laws can be checked. If one adopts the position expressed by the weaker principle MGP in §.V, the proofs of the Bell-KS theorem cannot be completed because one cannot assert that f(a, b,...)=0 and g(a′, b′,...)=0 hold simultaneously. Hence the repeated application of the KS condition implies postulating the unrestricted simultaneous validity of all empirical quantum laws, that is, MCP.

To conclude this section, let us note that the adoption of MCP can be defended by observing that physicists can choose the empirical law that they want to check among the laws listed in Eqs. (3). Since all experiments show that, for every choice, quantum predictions are fulfilled, it is difficult to understand how a breakdown of a law in Eqs. (3) may occur just when another law is experimentally proven to hold (*conspiracy of nature*[12]). We show in §.VIII, however, that this argument can be overcome by suitably reinterpreting quantum probabilities.

VII

Our analysis in §.VI can be repeated by considering further theorems of the same kind, as the Bell theorem (Garola and Pykacz 2004, Garola and Solombrino 1996a, Garola and Solombrino 1996b). Our conclusion can be resumed and integrated as follows.

(i) The deduction of fundamental and universally accepted theorems which state the contextuality and nonlocality of QM requires the adoption of an epistemological position (MCP) that assumes the validity of empirical laws also in physical situations in which the laws cannot, in principle, be checked. On the other hand, MCP necessarily follows whenever RTE is assumed and extended to relations on the set of theoretical entities formalized by means of L_T (*realism of theories*; Boniolo and Vidali 1999). Hence the adoption of MCP constitutes a clue, if not a proof, that RTE has been more or less implicitly accepted.

(ii) The contextuality of QM entails that, for every state of a physical system, nonobjective physical properties exist (§.VI). It follows that RTE (which implies MCP, hence the contextuality of QM) prevents one from adopting in QM any form of realism assuming objectivity of properties of physical objects. In particular, RTE does not allow one to adopt *semantic realism* in QM, i.e., a purely semantic form of realism which avoids ontological commitments and only assumes that every sentence attributing a property to a physical object is *semantically objective*, in the sense that it can be provided with a truth value

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[12] See, e.g., Laloë 2001.

(true/false). This result is relevant because the opposition between RTE and semantic realism is *a priori* unexpected, for it does not occur in classical physics and characterizes QM.

(iii) A change in the epistemological perspective (in particular, the replacement of MCP with MGP) may invalidate some deeply-rooted beliefs, opening the way to new interpretations of the formalism of QM (in particular, an interpretation in which semantic realism is assumed, hence contextuality and nonlocality are avoided).

VIII

An interpretation of the kind conjectured in §.VII, (iii), has been propounded several years ago by one of the authors, together with other authors (*semantic realism, or SR*, interpretation[13]). Successively various models have been provided to show the consistency of this interpretation. The last of these, named *extended semantic realism* (ESR) model, is a new kind of noncontextual hidden variables theory for QM which introduces, besides hidden variables, a reinterpretation of standard quantum probabilities.[14] The ESR model modifies (and in some sense extends) the original SR interpretation, but preserves its basic features, that is, semantic realism and the substitution of MCP with the weaker principle MGP. Within this model many problems (e.g., the *objectification problem* of the quantum theory of measurement[15]), paradoxes (e.g., the *EPR paradox* and the *Schrödinger's cat paradox*) and the ambiguities illustrated in §.IV disappear. These results are interesting not only from a physical point of view (interpretation of entanglement, quantum information, etc.) but also from a philosophical perspective. Therefore we devote this section to illustrate the main features of the ESR model.

The basic set of theoretical entities introduced by ESR model is a set $\mathcal{E}$ of hidden variables, whose elements are interpreted as *microscopic properties* (some additional parameters may occur that we do not discuss here). Given a physical object x and a microscopic property f, x either possesses or does not

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[13] See Garola and Solombrino 1996a, 1996b.

[14] See Garola 2002, 2003, 2007, 2009a, Garola and Pykacz 2004, Garola and Sozzo 2009a, 2009b, 2010a, 2010b, Sozzo 2007, Sozzo and Garola 2010.

[15] See, e.g., Busch et al. 1991.

possess f. The set of all microscopic properties possessed by x then defines the *microscopic state* of x.

Each f∈E corresponds to a *macroscopic property* F. If F is measured on x and x displays F, then x possesses f. But the converse implication does not hold, because the set of microscopic properties possessed by x (that is, the microscopic state of x) might be such that x cannot be detected when F is measured, independently of the specific features of the apparatus measuring F. Hence a *detection probability* is associated with the measurement of F which depends on the microscopic state of x, not only on F, and must not be mistook for the detection probability that occurs because of the reduced efficiencies of real measuring apparatuses.

The introduction of detection probabilities depending on the microscopic state characterizes the ESR model. The model does not say anything about the deep causes of them: rather, introduces them as overall results of these causes. Intuitively, one can think that "something is happening" at a microscopic level which underlies the standard quantum picture of the physical world and does not reduce to it, so that a broader theory is needed. The ESR model aims to be a first step in this direction.

The macroscopic part of the ESR model (briefly, the *macroscopic ESR model*) rests on the features of the microscopic part specified above, but it can be presented without mentioning hidden variables, as a self-consistent theoretical proposal. In particular, detection probabilities occur in it that can be considered as unknown parameters whose value is not predicted by any existing theory. More generally, the main features of the macroscopic ESR model can be summarized as follows.[16]

(i) It brings into every measurement a *no-registration outcome* which is interpreted as providing information about the microscopic world that is inquired, as well as any other possible outcome, hence it substitutes the observables of QM with *generalized observables* with enlarged sets of possible values.

(ii) It embodies the mathematical formalism of standard (Hilbert space) QM into a broader *noncontextual* framework, which explains how the objectification problem and the quantum paradoxes quoted above can be avoided.

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[16] See in particular Garola and Sozzo 2009b.

(iii) It reinterprets the quantum rules for calculating the probability that a physical object x in a state S display a property F when a measurement of F is performed as referring to a selection of x in the subset of all physical objects that have been prepared in S and can be detected (*conditional probability*) rather than in the set of all physical objects prepared in S (*absolute probability*).[17]

(iv) It provides some predictions that are formally identical to those of QM but have a different physical interpretation and further predictions that differ also formally from those of QM. Therefore it can be empirically checked, hence it is *falsifiable*.

(v) It implies, by introducing some additional assumptions, that the *Bell-Clauser-Horne-Shimony-Holt* (*BCHSH*) inequality, a *modified BCHSH inequality* and (reinterpreted) quantum predictions hold together because they refer to different parts of the picture of the physical world supplied by the model, hence it overcomes the opposition between the BCHSH inequality and the formal apparatus of QM in a framework in which physical properties are (semantically) objective, hence *local realism* (Bell 1964; Einstein, Podolsky and Rosen 1935) holds.

(vi) It introduces a kind of *unfair sampling* that explains the breakdown of the BCHSH inequality at a macroscopic level.

By formulating the foregoing theoretical proposal in mathematical terms, we have recently obtained some further relevant results in the ESR model.[18]

(a) Each generalized observable is represented by a (commutative) *family* of positive operator valued (POV) measures parametrized by the set of all pure states of the physical system that is considered. It follows that every physical property is represented by a family of bounded positive

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[17] This reinterpretation of quantum probabilities allows one to explain, without resorting to any conspiracy of nature, how it may occur that an empirical quantum law may fail to be true whenever another empirical quantum law is checked and proven to hold. Indeed, a physical object x that is detected when measuring, say, the observables A, B,... in Eqs. (3), which implies that the equation f(a, b,...)=0 must hold, could possess such microscopic properties that it would not be detected if instead the observables A′, B′,... were measured, hence one cannot assert that the equation g(a′, b′,...)=0 must also hold. But, of course, if A′, B′,... were measured and x were detected, then g(a′, b′,...)=0 would hold, because quantum laws hold for every detected object according to the ESR model.

[18] See in particular Garola and Sozzo 2010a.

operators (*effects*) rather than by a single projection operator, hence pure states can never be identified with atomic properties and the problems pointed out in §.IV, Examples 1 and 2, are avoided.

(b) A *generalized projection postulate* (*GPP*) rules the transformations of pure states induced by nondestructive idealized measurements.

(c) The conciliatory conclusion mentioned in (v) can be recovered without introducing additional assumptions.

(d) Each mixture is represented by a *family* of density operators parametrized by the set of all properties characterizing the physical system that is considered.

(e) The new representation of mixtures avoids the problems pointed out in §.IV, Examples 3 and 4. Indeed, proper mixtures having different operational definitions are represented by different families of density operators, even if they are probabilistically equivalent, which avoids problems (i) and (ii) in Example 3. Moreover, the distinction between proper and improper mixtures does not occur because all probabilities are epistemic, which avoids the problem sketched in Example 4.

(f) A *generalized Lüders postulate* (*GLP*) that generalizes *GPP* rules the general transformations of states induced by nondestructive idealized measurements.

(g) *GPP* can be (partially) justified by describing a measurement as a dynamical process in which a *nonlinear* evolution occurs of the compound system made up of the (microscopic) measured object plus the (macroscopic) measuring apparatus.

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