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From Wave-Particle to Features-Event Complementarity

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Abstract The terms *wave* and *particle* are of classical origin and are inadequate in dealing with the novelties of quantum mechanics with respect to classical physics. In this paper we propose to substitute the wave-particle terminology with that of features-event complementarity. This approach aims at solving some of the problems affecting quantum-mechanics since its birth. In our terminology, features are what is responsible for one of the most characterizing aspects of quantum mechanics: quantum correlations. We suggest that an (*uninterpreted*) basic ontology for quantum mechanics should be thought of as constituted by events, features and their dynamical interplay, and that its (*interpreted*) theoretical ontology (made up by three classes of theoretical entities: states, observables and properties) does not isomorphically correspond to the uninterpreted ontology. Operations, i.e. concrete interventions within the physical world, like preparation, premeasurement and measurement, together with reliable inferences, assure the bridge between interpreted and uninterpreted ontology.

Keywords Complementarity · Features · Interpreted and uninterpreted ontology · Equivalence class · Operation · Potentiality

1 Introduction

The terms *wave* and *particle* are of classical origin and turn out to be inadequate to deal with the problems of quantum mechanics. This means that since almost eighty years, they have represented a heavy load on any attempt at dealing with the interpretation of this theory. Indeed, notwithstanding the huge successes of quantum mechanics as a predictive theory, its interpretation, and therefore an understanding of the true nature of the entities postulated

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by the theory, is still unachieved. Our point of view is that this discipline raised so many fundamental questions and obliged such a profound revision of the epistemology and ontology characterizing the physical sciences for many centuries, that the problem could have been better approached through an appropriate interaction between philosophers and scientists. As a matter of fact, prominent scientists—like Bohr, Einstein, Heisenberg, Schrödinger—have tried to provide a philosophical framework for some problems. In this way, many important results were found. However, these frameworks were themselves fragmentary or not sufficiently general.

The main issue of the interpretation of quantum mechanics is what its ontological reference is, if any. The problem arises because it is not clear how to define a satisfactory concept of "physical system" that does not contradict the requirements imposed by quantum mechanics. A very broad definition could be: A physical system is an object or a collection of objects (somehow interrelated) that can be (directly or indirectly) experienced. This definition would surely satisfy those requirements. However, we would also expect something more from the concept of physical system, especially if we would like it to be the basic ontological referent of the theory. In classical mechanics, it is indeed a basic concept characterized by permanency and perfect instantiation (determination) of all of the properties that could be meaningfully assigned. The state of the system can be understood as the temporal section of its "history". Even if some compound systems may be transitory, in classical mechanics it is assumed that some basic elements will be permanent.

When we consider quantum mechanics, on the contrary, three different reasons to put in question the very notion of physical system as understood by classical mechanics can be found. First, photons can be annihilated or created, and even particles like electrons can be converted (together with positrons) into light quanta as well as be generated from photons. This prevents the possibility to assume the existence of a quantum system independently of the environmental context. Second, quantum particles are identical particles, that is, they can be interchanged and are actually not distinguished in many situations since the wave function may be the same (bosons) or the same with a change of the relative phase (fermions). This raises a serious problem of *indecidability* about which individual system we are dealing with. Finally, entanglement casts an *ambiguity* on the very notion of physical system. It is, indeed, impossible to know, from a pure local point of view, whether a certain system is entangled with other ones or not. This makes a considerable difference. In classical mechanics we are very often absolutely free to consider either a whole compound system or its parts as the object system, due to the fact that any classical compound system is a pure assembly of its parts: This is the content of the separability principle [12]. When, on the contrary, entanglement is involved, the whole entangled system should be considered as a single system rather than as a compound: The characteristics of an entangled system cannot be deduced from those of its components. These three points rise, therefore, serious doubts about the applicability of the notion of physical system as the fundamental ontological referent of the quantum theory.

This blocks the attempt at interpreting quantum systems as waves and/or particles provided of a classical meaning [10]. It is true that further developments due to Bohm [6, 7] have reinterpreted this view along the lines of a non-local theory that is alternative to both quantum and classical mechanics. However, we are not concerned here with theories alternative to quantum mechanics but wish only to point out that also this attempt is not exempt from problems [5, Chap. 16].

These difficulties explain the fact that many physicists have even renounced any ontology for quantum mechanics, thus arriving to the conclusion that the formalism is the only thing that does matter. One of the first examples of this attitude can be found in Heisenberg's early works [15]. We think, instead, that any fundamental physical theory, like quantum mechanics nowadays, must achieve the greatest clearness on its fundamental terms. Note that the EPR paper, and the immense debate that followed (and still follows) it, is a patent example of how such conceptual, interpretative questions may have enormous consequences on the development of a scientific disciplines. This fact shows that, when a fundamental physical theory is concerned, it is not only the formalism to be important; rather the basic ideas are what really counts. Moreover, the history of science provides a number of cases in which ideas come first and the formalism is only later elaborated to handle the ideas properly. Our work wants to be an effort in understanding the quantum formalism in the light of the relevant underlying concepts and ideas, a work that, it seems to us, has not still been performed completely.

The difficulty in finding a proper ontological reference of quantum theory also explains why, among the physicists who have not renounced an ontology, some have assumed that only events are real and are the only referent of the theory [1, Parts 4, 5]. This is the case for many experimentalists, like Anton Zeilinger [23, 24]. At the opposite, the supporters of the so-called many world interpretation [11, 13] seem to assume both that the only reality is represented by quantum-mechanical non-local features and that localized objects are illusions. However, events are in themselves meaningless; they tell nothing about anything, unless they are understood thanks to a *theory*. They simply happen and are therefore a piece of *uninterpreted ontology*. History of science shows this point very well: A number of phenomena, local happenings, and events can tell us different things about the world *according* to the theory we look at them [19]. On the other hand, to assume that everything is a pure illusion but the Universal Wave Function does not seem adequate to describe our experience of actual events and not very useful for dealing with many physical problems.

We should also consider the accumulation of many misunderstandings. Apart from the mentioned usage of the wave-particle terminology, we recall that classically the only acknowledged reality was actual reality. This is quite good when dealing with objects like watches but it is not adequate when trying to explain processes in which (in a certain time window) no event at all occurs and therefore no actual reality either, and nevertheless something finally comes out (for instance, a detection event happens) [22]. We shall claim that such situations are more suitably understandable resorting to an appropriate notion of *potential* reality. Moreover, classically there was a lack of distinction between law-dimension and event-dimension. In other words, when quantum mechanics was built as a physical theory, all physicists believed that laws directly rule individual systems and events. This is the reason why Bohr [8] still identified determinism (a typical law-aspect) with causality (a typical relation between actual entities). This identification made it extremely difficult to accept that quantum-mechanical laws—even not having a statistical nature—rule probability distributions of events and not the events themselves. Finally, a big confusion stemmed from the fact that physical magnitudes and properties were understood as describing true qualities of the objects. It was then difficult to understand how it is possible that there is a more or less determination of these magnitudes in a certain physical state of a given system, according to the uncertainty relations [15]. We shall show that physical magnitudes, properties and even states should be meant rather as theoretical notions by means of which we do speak of reality but without the claim that they *isomorphically correspond* to something real in the deepest sense. This will bring us toward a moderate and non-*naive* realistic attitude.

2 Epistemological Considerations

As we have said, a fundamental physical theory like quantum mechanics should not be reduced to pure formalism, since many interesting problems and questions arise from the investigation of its ontological import. Moreover, a fundamental theory should be able to tell us something about reality. One of the main epistemological questions is about *how* it tells us something on the physical reality. One should *not* think that a physical theory, in general, provides us with a sort of picture of the fundamental reality; especially in quantum mechanics this does not seem to be the case. We think that a theory provides an *interpreted* ontology by means of the theoretical entities it encompasses.

The reference of the theoretical entities should not be thought of as an isomorphic map to the elements of the underlying reality. Theoretical entities (and a theory in general) only need to have some connections with reality, i.e. a form of *controlled access* to them. This is provided by the operations (like measurement) that represent the bridge between the theoretical entities (and the formalism) and its ontological referents: Thus, operations provide the scaffold of suitable procedures for dealing with the entities that are object of the theory and, in turn, theoretical entities (together with the formalism) are ways to understand a reality that is for the great part unobservable as such but which, through those procedures and relative apparata, one can interact with.

All that is also connected with what we said above about the notion of physical system. In classical physics it is assumed that the physical system as defined by the theory—i.e., considered as a theoretical entity—*correspond* to the "*real*" system. Quantum mechanics, on the contrary, seems to us to suggest a position that is only moderately and *non-naively* realistic with respect to the physical theories. Theories are *not* pictures of reality; rather, they are tools enabling to *infer* some basic aspects of reality in a non-descriptive way. We shall come back to these points at the end of the paper.

3 Algorithms

Quantum theory is very appropriate in describing microsystems allowing for correct predictions of their behavior. We recall some very essential points. For the sake of simplicity, we consider a two-level system. Let us consider a system's state having the form

$$|\psi\rangle = c_x|x\rangle + c_y|y\rangle. \tag{1}$$

A state of this form is a quantum *superposition*. Let us assume here that $|x\rangle$ and $|y\rangle$ represent the eigenstates of some observable $\hat{O}$, and that they are associated with eigenvalues $+1$ and -1, respectively. Since in physics a *property* is the value of a physical magnitude, these eigenvalues represents possible properties of the system. To these properties possible outcomes are associated when the observable

$$\hat{O} = \hat{P}_x - \hat{P}_y \tag{2}$$

is measured. The probabilities to obtain these two outcomes ($\hat{P}_x$ and $\hat{P}_y$) are given by

$$\wp(x) = |c_x|^2 \quad \text{and} \quad \wp(y) = |c_y|^2, \tag{3}$$

respectively. A state of the form (1) contains not only the probabilities to obtain certain outcomes but also additional terms that have no classical analogue. They are commonly called *interference terms*, and express the fact that there are non-classical interdependences among these possible outcomes. To see this, let us consider the density matrix corresponding to the state (1), that is,

$$\begin{aligned}\hat{\rho} = |\psi\rangle\langle\psi| &= |c_x|^2|x\rangle\langle x| + |c_y|^2|y\rangle\langle y| \\ &\quad + c_x c_y^*|x\rangle\langle y| + c_x^* c_y|y\rangle\langle x|. \end{aligned} \tag{4}$$

The first line represents the true possible outcomes (and their associated properties), which can in principle be experienced as actual events. Instead, the (interference) terms appearing in the second line do not represent possible outcomes. Therefore, no single event can occur that can make directly experienceable the reality of these interference terms. This can be seen by noting that

$$c_x c_y^* \quad \text{and} \quad c_x^* c_y \tag{5}$$

are not probabilities in any sense. Notwithstanding, they both determine the specific nature of the quantum state and concur to the events that can be obtained, as we shall stress below. For these reasons, let us distinguish terms like those from true properties and call them *features*. The primary reason for using this word is that a specific term for denoting specific quantum correlations does not currently exist.

The probability amplitudes evolve in time. We have essentially two algorithms that describe this dynamics, the Schrödinger picture and the Heisenberg picture (we do not consider here the Dirac or interaction picture, since it is more interesting when dissipation phenomena occur). In the first picture [21], it is the state which evolves in time while the observables remain constant. In this case, we have the well-known Schrödinger equation, a first-order differential equation of the form

$$\imath\hbar\frac{\partial}{\partial t}|\psi\rangle = \hat{H}|\psi\rangle, \tag{6}$$

where $\hat{H}$ is the Hamiltonian of the system. By integration, this equation may also be rewritten as

$$|\psi(t)\rangle = e^{-\frac{\imath}{\hbar}\hat{H}t}|\psi(0)\rangle, \tag{7}$$

where $|\psi(0)\rangle = |\psi\rangle$ is the state vector at time $t = 0$. The time evolution operator

$$e^{-\frac{\imath}{\hbar}\hat{H}t} = \hat{U}_t \tag{8}$$

is a unitary operator, which is an hallmark of reversibility.

The Heisenberg picture [14] can be derived from this formalism by considering the mean value of the observable $\hat{O}$ at time t, that is, by taking into account the expressions (7) and (8), we obtain

$$\begin{aligned}\langle\psi(t)|\hat{O}|\psi(t)\rangle &= \langle\psi(0)|\hat{U}_t^\dagger\hat{O}\hat{U}_t|\psi(0)\rangle \\ &= \langle\psi|\hat{O}(t)|\psi\rangle, \end{aligned} \tag{9}$$

where in the last line the vector $|\psi\rangle = |\psi(0)\rangle$ has been again considered without time dependence, and the observable

$$\begin{aligned}\hat{O}(t) &= \hat{U}_t^\dagger\hat{O}\hat{U}_t \\ &= e^{+\frac{\imath}{\hbar}\hat{H}t}(|x\rangle\langle x| - |y\rangle\langle y|)e^{-\frac{\imath}{\hbar}\hat{H}t} \end{aligned} \tag{10}$$

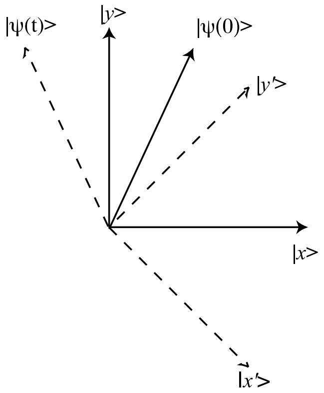

Fig. 1 A transformation may be considered from two viewpoints. As an active transformation (Schrödinger picture): Here, the state vector $|\psi(0)\rangle$ is counterclockwise rotated into the state vector $|\psi(t)\rangle$. And as a passive transformation (Heisenberg picture): Here, the reference frame is clockwise rotated from the basis vectors $|x\rangle, |y\rangle$ to the vectors $|x'\rangle, |y'\rangle$ about the same angle

evolves in time in the Heisenberg picture. Due to the unitary transformation (10) from the Schrödinger to the Heisenberg picture, these two algorithms can be considered fully equivalent descriptions of the dynamics of a quantum system. Their relationship is shown in Fig. 1.

The important point to stress here is that these two algorithms (the Schrödinger and the Heisenberg pictures) only rule the above evolution of the coefficients. Therefore, *these algorithms have nothing to do with actual events* as such. This also means that events are random. For instance, we can tell in the mean how long it takes for a piece of radioactive matter to decay but we cannot predict when a single atom will decay.

4 Events and Features

4.1 Delayed-Choice Experiment and Non-local Correlations

We have shown the difficulties of speaking of the quantum system as the basic ontological entity of the theory. Now, we shall consider the same problem from a slightly different point of view. The so-called delayed choice experiment [22] shows the fundamental quantum result that we cannot speak (not even at the level of the definition) of a phenomenon without interacting in some form with it. Using Wheeler's words, we can state that "no elementary phenomenon is a phenomenon until it is a registered (observed) phenomenon".

Wheeler's original proposal [Fig. 2] is the following: In a Mach-Zehnder-like set up, the detectors may be switched from positions $\mathrm{D_A}, \mathrm{D_B}$ to positions $\mathrm{D'_A}, \mathrm{D'_B}$ and *vice versa*. This may be done after the photon has already passed the first beam splitter (BS1). In the arrangement $\mathrm{D_A}, \mathrm{D_B}$ we detect the path of the photon, whereas in the arrangement $\mathrm{D'_A}, \mathrm{D'_B}$ we detect the interference.

Taking into account this experimental set-up, there are time intervals (in the case shown in Fig. 2, the time interval in which the photon travels from BS1 to the detectors), where we cannot assume that an event happened, whereas, after this interval, an event may have occurred (the photon has been registered). However, would this mean that, before detection, there is no reality at all? If this were the case, an event would appear from nothing [4]. It is true that according to the previous section, an event is a pure random happening in quantum mechanics. However, it seems impossible that we have a detection event without having beforehand some reality that could subsequently be detected. How to solve this puzzle? What is the minimal—not event-like—reality that we are obliged to assume in any case? This minimal reality consists in the non-local correlations between the components represented

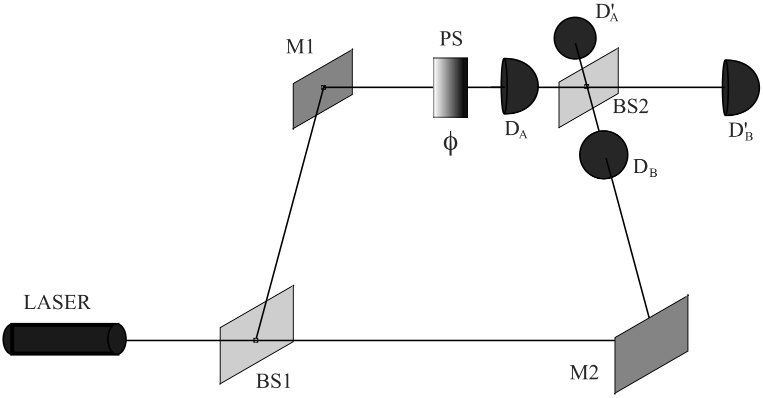

Fig. 2 Interferometry experiment for testing delayed-choice. The set up is essentially a Mach-Zehnder interferometer in which the two detectors may be switched from positions $\mathrm{D_A}, \mathrm{D_B}$ (which–path detectors) to positions $\mathrm{D'_A}, \mathrm{D'_B}$ (interference detectors). This decision will be taken after the photon has already passed through BS1

by the two paths allowed for a photon to reach the detectors. Of course, after BS1 the photon is in a quantum superposition between these two alternatives. Note that these components, as far as there is no detection event, have no reality in themselves, and therefore we are not allowed to assume other reality than the pure correlations (*features*). In other words, the general lesson taught by the delayed-choice experiment is that, after the first beam-splitter, to speak of "the system" passing through the apparatus is highly problematic. We also mention that a series of experiments led by H. Rauch shows that even when there is no interference in the configuration space, interference effects are not lost in the momentum space [20].

Thus, delayed-choice forces us to think that reality cannot be made only of a collection of events. Our proposal is that an ontological import must be attributed to correlations as such and, therefore that reality should be interpreted as a dynamical interplay between local events and non-local features. Local events and non-local features—*rather than* waves and particles—should be considered complementary. There is a further evidence for the ontological import of features: Quantum mechanical systems may have a negative conditional entropy that can be interpreted as potential to transfer additional quantum information in the future at no further cost [17], making use of entangled bits (ebits), which are another manifestation of features. Summing up, we propose therefore to substitute the wave-particle dichotomy with the features-event one *by claiming* that features cannot be directly detected but that their *existence* can be *inferred* thanks to experimental outcomes with the help of a suitable interpretative framework.

4.2 A Possible Experiment: Enquiring the Reality of Features

We have now to see which are the crucial positive reasons to consider features as fundamental *ontological* elements of the quantum world. Indeed, in experiments on complementarity proposed and realized up to now, the interference profile could be reconstructed only after many experimental runs, leaving therefore the door open to the objection that features are not actually real. This tricky situation can be overcome by considering a proposed experiment in which detection events allow to infer the non-local correlations at any *single* run [3]. This proposed experiment was originally conceived to show that some form of reality

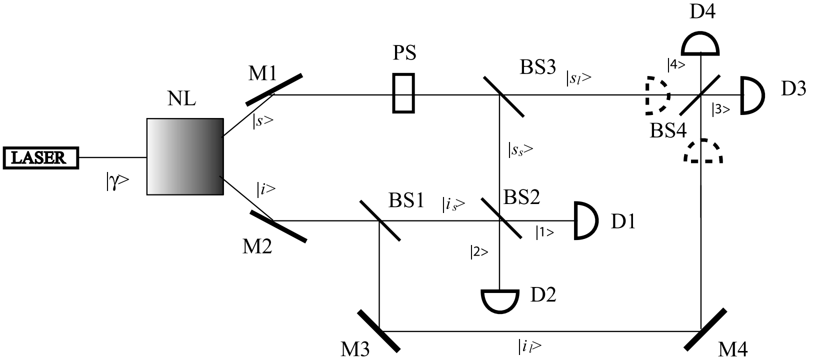

Fig. 3 A source laser pumps a photon in the state $|\gamma\rangle$. Successively, a parametric-down-conversion allows the emission of two photons, the *idler photon* (in the state $|i\rangle$) and *signal photon* (in the state $|s\rangle$). If γ has frequency ν and energy $h\nu$, the two outgoing photons have smaller frequencies ν_i and ν_s (and energies $h\nu_i$ and $h\nu_s$), respectively, with $\nu = \nu_i + \nu_s$. The two beam splitters BS1 and BS3 split each photon into two components, the 'shorter' and 'longer' components ($|i_s\rangle, |i_l\rangle$ and $|s_s\rangle, |s_l\rangle$, respectively). The two shorter (longer) components, $|i_s\rangle$ and $|s_s\rangle$ ($|i_l\rangle$ and $|s_l\rangle$) are recombined at BS2 (BS4), giving rise to photons in states $|1\rangle$ and $|2\rangle$ ($|3\rangle$ and $|4\rangle$), falling to detectors D1 and D2 (D3 and D4). Eventually, detectors D3 and D4 are placed before BS4 when D1 or D2 has already clicked

can be attributed to quantum waves (Fig. 3). According to what said in the previous subsection, however, we are now inclined to interpret it as supporting the reality of *features*.[1] The proposed experiment we are going to describe, by making features directly linked to coupled events in a *single* run, provides evidences for the existence of non-local features in *each* experimental run.

Let us consider the experimental set-up with some details. A laser (on the left) pumps a photon at-a-time into the non-linear crystal NL. The two outgoing photons (with the same frequency and in general in the same state) are called, as usual, *idler photon* (*i*) and *signal photon* (*s*). The s-photon goes through the beam splitter BS3, then it follows a shorter and a longer path. The i-photon undergoes an analogous transformation after it has gone through BS1. At BS2 and BS4, components of both the i-photon and the s-photon are recombined and split again (finally reaching detectors D1 and D2, and D3 and D4). The beam splitters may be taken to be 50–50%. After the non-linear crystal and the first two beam splitters, the initial state evolves according to

$$\begin{aligned} |\gamma\rangle &\overset{\text{NL,M1,M2}}{\mapsto} |s\rangle|i\rangle \\ &\overset{\text{BS1,BS3}}{\mapsto} -\frac{1}{2}[(|s_s\rangle + |s_l\rangle)(|i_s\rangle + |i_l\rangle)], \end{aligned} \tag{11}$$

where the subscripts s and l indicate the shorter and the longer path, respectively. After the mirrors M3 and M4 and the two final beam splitters we obtain the final state

$$\begin{aligned} &\overset{\text{M3,M4,BS2,BS4}}{\mapsto} \frac{1}{4}[(|1\rangle - |2\rangle) + (|3\rangle + |4\rangle)][(|1\rangle + |2\rangle) + (|3\rangle - |4\rangle)] \\ &= |f\rangle. \end{aligned} \tag{12}$$

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[1] Note that, even in the original proposal, waves were conceived as responsible for the establishment of non-local correlations and not as something similar to classical waves—whose main physical character is that of carrying energy.

This state in its unnormalized form, can be rewritten as

$$|f\rangle = \frac{1}{4}(|1\rangle|1\rangle - |2\rangle|2\rangle + |3\rangle|3\rangle - |4\rangle|4\rangle + 2|1\rangle|3\rangle + 2|2\rangle|4\rangle). \tag{13}$$

Such a state is a very interesting one. If we discard the cases in which both photons are detected by the same detector and only consider the cases in which, for each photon pair, the two photons are detected by different devices (by performing a postselection preserving only the cases of the lower line of the (13)), we obtain that, when detector D1 clicks, detector D4 must click as well, and when detector D2 clicks, detector D3 must also click. Here, we have a special kind of EPR state [12], which, in its standard normalized form, may be written as

$$|f'\rangle = \frac{1}{\sqrt{2}}(|1\rangle|3\rangle + |2\rangle|4\rangle). \tag{14}$$

It is interesting to stress that because of this entanglement, we cannot know which photon has been detected by which detector, although thanks to the entanglement, we can predict with certainty whether detector D3 or detector D4 will click once either detector D1 or detector D2 has clicked. Moreover, the possibility to predict with certainty if D3 or D4 will click on the basis of what happens at D1–D2 suggests that the features characterizing the entangled state (14) are *responsible* for such a situation. With *responsible* we understand a reality able to canalize certain results in such a way that, given additional dynamic conditions, predictions become possible, even though such a reality is not able by itself alone to produce these effects.

4.3 Features and Potentiality

Let us now discuss the reasons why ascribing reality to the features may sound so astonishing. Classically, the only acknowledged reality is actual reality. This also means, as we have seen, that a classical physical system is considered actual as such. In quantum mechanics there is also actual reality, for instance detection events. An *event* is quantum-mechanically a reality, which, for its realization, needs the concourse of several systems and which, *de facto*, can be experienced through its immediate effects. It is essentially random and is not ruled by the algorithms (only its probability to occur is ruled by them). However, as we have seen, in quantum mechanics algorithms can be barely asserted to be the only form of reality.

We propose to consider quantum features as a form of potential reality (as Heisenberg [16] already suggested). By *potentiality* we understand that kind of non-actual and relational reality thanks to which, if activated by suitable actual external conditions (that is, conditions that do not depend on, nor are controllable by, the system), one arrives to an actual event. These external conditions are in a general sense environmental conditions (including but not restricted to experimental apparata) [18, 25, 26]. Summing up, features are potential realities as far as:

- They represent a necessary ingredient of any quantum-mechanical interaction process (they play a key role in premeasurement, as we shall see).
- When activated, they contribute to the actualization of possible outcomes (see Sect. 4.2).
- Some actual environmental conditions (including apparata) are also necessary for one of these outcomes to occur, resulting in some event.

In other words, features are *activated* in certain contexts to give rise to certain consequences, thus showing the capability of contributing to determine actual reality. In conclusion, to use the term *feature* has a double advantage: It stresses that we deal with a reality (although potential) and it may be used to address all of the different quantum non-local phenomena.

5 Operations

Preparation, premeasurement, and measurement constitute the three fundamental operations a system can undergo in quantum mechanics. Such operations should be thought of as concrete interventions on the physical world that can somehow affect the system at hand [9]. Note that this does not imply at all any subjectivism, since analogues of the three operations can happen spontaneously in nature. The only difference between the operations and their spontaneous analogues is that the former, being instantiated in a controlled way, allow us for making inferences about the system(s).

5.1 Preparation

A state of the form (1) can always be *prepared*. For instance, the state $|x\rangle$ may represent horizontal polarization, while the state $|y\rangle$ may represent vertical polarization. Then, the state $|\psi\rangle$ may be some polarization orientation, determined by the coefficients c_x and c_y. When they are equal, the state $|\psi\rangle$ expresses a polarization at 45°. If we want to prepare a system in a 45°-polarization state we have to let systems pass a filter with such an orientation.

A preparation can be understood as a *determination* of the *state* of a single *system*. It is the procedure through which only *systems in a certain* (previously theoretically defined) *state are selected* and delivered for further procedures, that is, allowed to undergo subsequent operations (premeasurement and measurement).

5.2 Premeasurement

A premeasurement consists in an *interrogation* of a quantum system relative to a specific degree of freedom. Quantum mechanics seems to imply that the specific basis used for the expansion of the compound state of the apparatus and the system is irrelevant, and therefore that premeasurement is not about a specific observable. The fact is that, at a rather abstract level, several bases for a state of two coupled systems are possible.

This also reflects the equivalence of the Schrödinger and Heisenberg pictures in describing the evolution of the compound system. However, we should not mix measurement *procedures with algorithms*. When we consider a specific physical situation (that is, once a premeasurement is done), we introduce a further degree of determination and are no longer authorized to treat different experimental contexts as equivalent.

Therefore, it would be highly unphysical to consider all observables as equivalent *in a concrete experimental context* since, changing the apparatus' basis means a concrete change in the apparatus as such, so that we may no longer assume to have to do with the same or an *equivalent* measurement process. For this reason, choosing a *certain* experimental context univocally individuates a *certain* observable. This is exactly the reason why we said (in Sect. 4.3) that *actual* external conditions are needed to obtain an event. That an experimental context individuates a certain observable (better, a certain degree of freedom) is also true, to a certain extent, from a classical point of view, since each apparatus is better suitable for measuring a certain observable and not others.

Finally, we stress that, as features are an intrinsic characteristic of entanglement and since premeasurement essentially consists in entangling the object system with the apparatus, features play an important role in premeasurement operations. In fact, taking an apparatus in an initial state $|a_0\rangle$ (the stand-by state), the insertion of the object system in the apparatus can be formally expressed by the following coupling between the two:

$$|\psi\rangle|a_0\rangle \mapsto |\eta\rangle = c_{x,a_x}(t)|x\rangle|a_x\rangle + c_{y,a_y}(t)|y\rangle|a_y\rangle, \tag{15}$$

where $c_{x,a_x}(t)$, $c_{y,a_y}(t)$ are some coefficients that, for our needs, are not to be specified. The state (15) represent an entanglement, and its density matrix, if explicitly stated, will reveal features formally similar to that of (5).

5.3 Measurement

Detection or measurement in a strict sense is an *answer* to our interrogation. When we establish an entanglement, we are actually entangling the object system also with some detectors. Although detectors are in general considered as part of an apparatus, they are conceptually very different. An apparatus is a *coupling* device, while a detector is a *selection* device. This justifies the fact that, properly speaking, the apparatus is an interface between detector and object system.

When a suitable selection is made, the detection apparatus is in one of its basis states and, upon the coupling with the object system, it tells information about the latter. This connection allows for a certain random outcome to tell us something about the input state.

On this basis, as already announced, we may consider that each step here (from preparation through premeasurement up to detection) can be considered as a further degree of determination, or the whole can be seen as a dynamical process through which, starting from some potential reality and suitable actual conditions, an actual reality (the event) is obtained.

6 Theoretical Entities

Since any state can be prepared using given procedures, we understand the state as an *equivalence class of preparations*. Indeed, different preparations can lead to the same state (they can be therefore considered equivalent) and also different systems may be prepared in the same state.

It is true that when a system is in a given eigenstate of an observable (say, $|x\rangle$), we often assume that it has the property associated with this state. However, in so doing, we are mixing two different issues.

- One thing is that the state is the complete catalogue of all probabilities that may be calculated (the algorithm level).
- Another issue is whether or not this state has already been subjected to the measurement procedures in order to establish whether it has this property or not (the operational aspect).

This distinction is very important. Indeed, a state $|x\rangle$, from a pure formal point of view, can be also considered as a superposition [2], for instance,

$$|x\rangle = |\psi\rangle + |\psi_{\perp}\rangle, \tag{16}$$

where $|\psi\rangle$ is given by the expansion (1) and $|\psi_{\perp}\rangle$ is given by

$$|\psi_{\perp}\rangle = c_x|x\rangle - c_y|y\rangle. \tag{17}$$

In other words, if the system would undergo another experimental procedure such that we measure the observable whose eigenstates are $|\psi\rangle$ and $|\psi_{\perp}\rangle$, the state $|x\rangle$ would no longer instantiate the property we assumed to be real. It would be indeed a weird situation if properties did appear and disappear depending on the expansion we are considering. In other words, properties are *never acquired* but only inferred given certain detection events. This obviously does not mean that the state is a pure formal object. However, it is an *interpreted* piece of ontology referring, in a non-mirroring way, to the deep and hidden dynamical interplay between features and events that is involved in any dynamic process between open systems.

An observable is a *physical magnitude*, that is, a collection of properties of the form (2). Following EPR [12], we can say that an observable is an interpreted *element of reality*. Indeed, it represents a "dimension" of the system through which the latter is defined. Moreover, since to measure a certain observable a number of slightly different concrete physical contexts could be equally good, an observable is an *equivalence class of premeasurements*. This sheds light on our examination in Sect. 5.2. The fact that an observable is an equivalence class of operations clearly supports that it is an element of reality, although interpreted.

We finally stress that properties may be operationally defined as *equivalence classes of events*. This also shows that properties cannot be identified with events, nor with any actual form of reality, and are rather inferred given a certain event and a certain coupling.

Both classical and quantum-mechanical states are equivalence classes of preparations, observables equivalence classes of premeasurements, and properties equivalence classes of events. The main difference is that quantum mechanical systems present non-local features that deeply affect the way we can define and treat the theoretical entities. Since in classical mechanics all observables commute, there is no conceptual distinction between event, property, observable, and state. Moreover, this gives the illusion that properties (and also physical magnitudes and states) can be directly identified with events and therefore are actual forms of reality. For this reason, quantum mechanics teaches us a quite general lesson, since the existence of features deeply affects the notion of the state (which is not simply a sum but a *combination* of properties), the definition of observables (they may not commute), and the conception of properties (they cannot be all compatible, but the possibility to infer some of them excludes the simultaneous consideration of other ones). Therefore, quantum theory prevents the illusion of identifying these physical concepts with directly experienceable, actual realities.

7 Ontologies

The uninterpreted and fundamental ontological elements that determine all the above characters of states, observables and properties (which are the components of the quantum mechanical *interpreted ontology*) are features, events, and their *dynamical interplay* (see Fig. 4). Why are features and events components of an uninterpreted ontology? Because, any piece of reality to which we may have an access is experienced by us through its (delayed) effects: e.g. we cannot obtain information about the big bag if not through the cosmic background radiation that we can measure today. Now, it is classically assumed that we can always circumvent this problem, at least in principle, through other chains of causes and effects through which the original event that gave raise to the effects that we may measure today can be considered to be itself a (deterministic) consequence of some other cause (in current cosmology to a certain extent this is assumed even for the big bang itself). Now, quantum events are random. We cannot find even in principle conditions or causes that may explain their singular occurring, and for this reason we are not able to control the modality of their happening. Features, on the other hand, are non-local correlations whose reality can only be inferred in ascertaining that certain statistical distributions would not otherwise happen. Now, somebody could say that this is true but we can assume that the dynamic interplay between events and features, at least, is a piece of interpreted ontology. We wish to stress

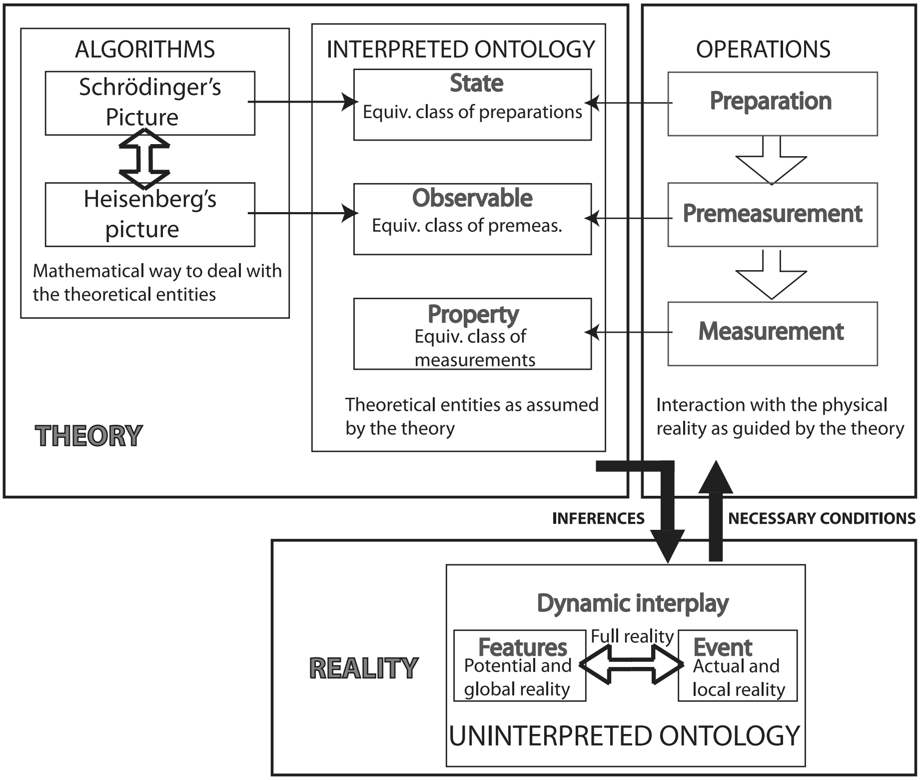

Fig. 4 Quantum mechanics as a theory is composed by the mathematical formalism (the algorithms) and the theoretical entities (states, observables and properties). The *double arrows* between the two pictures stands for their equivalence. They rule the evolution of states and observables (indicated by the *bold right arrows*). Operations are concrete interactions with the physical world guided by the theory. Preparation, premeasurement, and measurement can be understood as three successive degrees of dynamical determination of the involved physical system (*vertical empty arrows*): all of these determinations are therefore particular kinds (controlled forms) of dynamic interplay between events and features. States, observables, and properties are equivalence classes of preparations, premeasurements, and measurements, respectively (*thin left arrows*). The *double arrow* of the uninterpreted ontology means the dynamical interplay. Starting from theory it is possible to make inferences about the uninterpreted ontology (*top-down bold arrow*), based on experimental evidences; uninterpreted ontology can be seen as providing the necessary conditions to carry out successful interactions with reality, i.e. operations. The cycle theory-uninterpreted ontology-operation is what allows for both successfully interacting with the physical reality and reliably inferring something about the latter

that in a full sense of the word, reality can indeed be assigned only to this dynamic interplay. However, this dynamic interplay is the operational connection between what quantum theory aims to describe and the kind of elusive reality quantum systems represent, and therefore, from our point of view of scholars trying to describe and interpret quantum phenomena, is nothing else than the dynamical interaction that we have with a system through an apparatus and some detectors thanks to which we can make any ontological assignment as such. Then, again we cannot circumvent this essential limitation. It is also clear from the point of view of this interplay that the other two aspects are more unilateral and therefore *complementary*, and can be understood as local- and global-dependent, respectively [2]: From a global point of view, all is interrelated (only features do matter) and it is as no event happened. From a local point of view, we experience events and we do not perceive features at all. However, these two aspects are intimately connected and determine what we call reality.

Let us now have a closer look at Fig. 4. The *interpreted ontology* is made up by the theoretical entities. It represents the way we refer to reality in a non-mirroring way by making use of theoretical elements defined by the theory and within the mathematical formalism. The *operations* are concrete interactions with reality as guided by the theory. They are concretely performed interventions on the physical world carried out *as if* reality consisted of states, observables, and properties. The *uninterpreted ontology* consists of those necessary conditions, whose existence is required for obtaining the experimental outcomes that follow the whole sequence of operations (preparation, premeasurement and measurement). Hints at the existence of an uninterpreted ontology thought of as the dynamical interplay between features and events are given *by inferences* from what the theory (theoretical entities plus algorithms) tells us according to the available experimental data, *under the hypothesis* that such data are the consequences of a particular reality and the specific operations we perform. The uninterpreted ontology that should be accepted is the one able to make *reasonable* the experimental results at our disposal.

8 Conclusions

In this paper a new and general interpretation of quantum mechanics is suggested. We think that it is, at least in principle, able to solve all the problems listed in the introduction. It should appear clear that our interpretation is grounded upon both the distinction between *events* and *features* and a careful reconsideration of the idea of *potentiality*. Another fundamental point is the idea that a quantum event cannot be identified with a property: in general, an event allows us to infer a property; however, as we have seen, a single event might lead us to conclude different properties according to the whole experimental set-up (premeasurement *and* detection). Moreover, according to our interpretation, there is no reason to make use of the wave-particle terminology if not in a metaphoric way. Behind this terminology there is the complementarity features-events. The reason is that classical waves and classical particles are realities that can be thought about to be immediately accessible. On the contrary, quantum reality has an elusive character and we have stressed in particular that we cannot consider quantum events or features as specific effects of any particular cause and therefore not describable, even in principle, in terms of local properties and consequences. The confusion between these two different orders of consideration may explain many incongruences that have accumulated along the history of quantum mechanics.

One might object to our proposal that, being features potential and relational in character, and therefore not directly experienced, our attempt falls out of any empirical control. We would answer that the existence of features can be inferred and that empirical evidences (although *necessarily* indirect) for that might be provided by the proposed experiment treated in Sect. 4.2, whose main peculiarity is that of allowing for ascertain the presence of interference phenomena at any *single* experimental run.

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