

Event ontology in quantum mechanics and the problem of emergence

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We introduce an ontology of objects and events that is particularly well suited for several interpretations of quantum mechanics. It leads to an important revision of the notion of matter and its implications. Within this context one can show that systems in entangled states present emergent new properties and downward causation where certain behavior of parts of the system are only determined by the state of the whole. Interpretations of quantum mechanics that admit such an event ontology solve the problem of emergence.

I. INTRODUCTION: THE DERIVATION OF AN ONTOLOGY FROM PHYSICS

Classical physics has inspired an ontology that has had profound implications in the origins of modern philosophy. In this ontology one assumes certain robust associations of properties and objects. These associations have certain stability with respect to time and are independent of the specific sequence of observations. For instance sufficiently frequent measurements of the position of a particle give similar values and if one decides to measure other attributes between two measurements of positions the result remain unchanged. These hypotheses, valid in any classical ontology, led to Hume's conception of the world, so ingrained in contemporary philosophy. We will return to them later on.

To derive an ontology from the quantum theory has not been easy given its interpretational difficulties together with its conflict with the classical ideas. In spite of initial efforts by the leading founders of the field, dealing with the problem with an operational approach, questions have lingered. Within the Copenhagen Interpretation quantum mechanics is introduced in terms of measurements. Quantum systems do not have definite properties till they are measured. Between measurements their evolution is deterministic, as described by Schrödinger's equation, but in the measurements one has probabilistic behavior. In the standard presentation, one also has to assume that in the measurement processes the states change in a way not described by the Schrödinger equation. The difficulties to associate attributes to a quantum system independent of it being measured or not are in the core of the ontological problems presented by the quantum theory.

Perhaps the common characteristic between the different proponents of the Copenhagen Interpretation is precisely that facing certain ontological problems they retreat and stop any attempt to analyze the situation in fully realistic terms. As we have seen, this point of view appears very problematic to all those like Einstein, Schrödinger or Bell, who refuse to take instrumentalist positions. The acceptance without criticism of the Copenhagen Interpretation in its various versions has not favored the development of new ideas and questions and delayed the understanding of the most revolutionary aspects of quantum physics. It was only due to the immense intellectual stature of certain dissenters, as the ones we just mentioned, that these problems remained in the spotlight and allowed advances as those of Bell and the subsequent discovery of quantum decoherence. In the last decades this situation has changed because the investigation of topics of great conceptual importance, like those having to do with entanglement and decoherence, have opened new perspectives with remarkable potential practical applications like quantum cryptography or quantum computation. The advances have allowed to verify that many macroscopic systems have quantum behavior and the conviction that the quantum theory has universal validity has been reinforced. It has also become apparent that the different physical aspects related to the measurement problem like the interaction with the environment or the use of physical clocks are perfectly analyzable with the methods of quantum mechanics and should not be excluded at the time of seeking a more complete understanding of the problem.

A. The ontology of classical physics

For centuries the principles of classical mechanics as formulated by Newton and developed by Lagrange and Laplace were implicitly considered as the basis and foundation of the scientific conception of the Universe. The expectation was that the other sciences would eventually be reduced and explained in mechanical terms. Even though this goal was never achieved many areas of knowledge adopted a general mechanistic world-view. The mechanistic paradigm was superseded by relativity and quantum mechanics but it has been extremely prevalent until our days because of its simplicity and apparent consistency. The mechanistic paradigm is simple: matter is composed by elementary

components —particles— which are not altered when they combine to give rise to complex structures. Classical mechanics identifies the world as a succession of instantaneous configurations of systems of material points that occupy successive positions in the mathematical space of Euclidean geometry.

In this context, different phenomena produced by a system result from the different configurations that its component particles take. Given the laws of force, the motion obeys a deterministic evolution. Nothing new may occur in a classical system that is not determined by its initial configuration. In the classical world there is causal closure, every event is the consequence of preceding events without any freedom for novelty. The elements of the classical world are matter, the absolute space and time in which that matter moves, and the laws of force that govern movement. No other independent categories of being, such as mind, feelings or purpose are acknowledged. Cartesian dualism includes the mental aspects in terms of a new substance, being any possibility of interaction between the mental and the physical basically impossible to explain without ad hoc assumptions.

The discovery of an independent form of matter as the classical fields —for instance the electromagnetic one— did not change the basic foundations of the classical ontology. In particular classical fields have well defined attributes that can be measured at any time and the theory still is determinist. The notion of separability that is at the basis of Hume’s doctrine of supervenience [1] is still perfectly justified within the context of classical physics including fields. It establishes that “The complete physical state is determined by (supervenes on) the intrinsic physical state of each space-time point (or each point like object) and the spatio-temporal relations between this points.” In other words separability establishes that the total state of the Universe is determined by the states of its localized parts. As it was noticed by Teller [2] and stressed by Maudlin [1] this notion of separability no longer applies at the quantum mechanical level.

B. Quantum mechanics and the crisis in the ontology of classical physics

In the standard interpretation of quantum mechanics, the wave function is a representation of all our probabilistic knowledge about outcomes of possible measurements and as such is devoid of any ontological content: As Busch [3] puts it: “In other words in the standard interpretation, the formalism of quantum mechanics or the quantum algorithm does not reflect a well defined underlying reality, but rather it constitutes only knowledge about the statistics of observed results.”

The classical concepts are put in doubt by this interpretation but are not substituted by better, more suitable concepts. Faye, in The Stanford Encyclopedia of Philosophy [4] summarizes Bohr’s point of view as follows:

- “The interpretation of a physical theory has to rely on an experimental practice.
- The experimental practice presupposes a certain pre-scientific practice of description, which establishes the norm for experimental measurement apparatus, and consequently what counts as scientific experience. . . .
- This pre-scientific experience is grasped in terms of common categories like thing’s position and change of position, duration and change of duration, and the relation of cause and effect, terms and principles that are now parts of our common language.
- These common categories yield the preconditions for objective knowledge, and any description of nature has to use these concepts to be objective.
- The concepts of classical physics are merely exact specifications of the above categories.
- The classical concepts... are therefore necessary in any description of the physical experience in order to understand what we are doing and to be able to communicate our results to others, in particular in the description of quantum phenomena as they present themselves in experiments; ...”

But the consistency of the classical description is in this context in doubt because the line of separation between the quantum object and the measuring device is not the one between macroscopic instruments and microscopic objects. In fact, as Bohr himself pointed out, parts of the measuring device need sometimes to be treated in quantum mechanical terms in order to have a consistent description of the measurement processes.

II. AN ONTOLOGY OF STATES, OBJECTS AND EVENTS FOR QUANTUM MECHANICS

Attempts to base an ontology on events have a long history that was reinforced by relativity and the quantum theory. In relativistic physics events are considered points in space-time. The events of the relativistic universe

combine into partially ordered sets. An event B is to the future of another event A if it belongs to its future region defined by the light cone with vertex in A. In that case A can influence B. If B is outside the future light cone of A then it is causally disconnected with A since the maximum speed of propagation of a signal is the speed of light. The formalism of quantum mechanics makes reference to primitive concepts like system, state, events and the properties that characterize them. The use of these concepts suggests that the theory should admit an ontology of objects (understood as systems in given states) and events. The program of accounting for physical reality in terms of events has a long and noble tradition that goes back to Russell, who stated that [5] “the enduring thing or object of common sense and the old physics must be interpreted as a world-line, a causally related sequence of events, and ... it is events and not substances that we perceive.” To put it differently, for Russell an object is nothing more than a set of events that are causally connected. Although we consider this point of view a step in the right direction, we think it is incomplete for a foundation of physical reality based on events, particularly in the light of quantum mechanics.

A quantum system is described by a Hilbert space that represents the set of its possible states and the events that may occur in the system. Based on this ontology, objects and events can be considered the building blocks of reality. Objects will be represented in the quantum formalism by systems in certain states. In an event interpretation like the ones we are considering, events are the actual entities.

States describe the potentialities or dispositions of the systems for the production of certain events. The formalism of quantum mechanics associates a projector to each property or event. The element hydrogen is a quantum system. A particular atom is a system in a given state. It is an example of what we call object. It is characterized by its disposition to produce events on other systems: for instance the emission of a photon that produce a click in a photodetector. Note that for Russell an atom cannot be considered an object as long as it does not interact yielding events, whereas our definition naturally includes any microscopic object as an object given that its disposition to produce events is always defined by its state.

Concrete reality accessible to our senses is constituted by events localized in space-time. That is, by certain entities that occupy a small region of space-time. As Whitehead [6] recognized: “the event is the ultimate unit of natural occurrence.” Events come with associated properties. Quantum mechanics provides probabilities for the occurrence of events and their properties. When an event happens, like in the case of the dot on a photographic plate in the double slit experiment, typically many properties are actualized. For instance, the dot may be darker on one side than the other, or may have one of many possible shapes. The postulated association between properties and objects typical of the classical physics is now substituted by an association of properties with events. Objects understood as systems in certain dispositional state do not have properties until they are measured or produce events

There is only an exemption to this rule. One can in principle assign some properties to pure states. These properties are the ones observed during the preparation of the state. But, contrary to what happens in classical physics these associations are not independent of the specific sequence of observations performed on the quantum system. Thus one of the main postulates of classical ontologies as Hume’s one is no longer valid. This assumption, that was considered by Einstein at the root of the possibility of doing science¹ and the derived notion of separability we mentioned before do not apply to quantum physics that nevertheless is a rigorously formulated and tested theory.

The basic idea of a measurement is the occurrence of a macroscopic phenomenon, that is of something capable of reaching perception. Thus, as noticed by Omnès, the measurement of a property of a microscopic object implies making it generate a phenomenon, in other terms produce an event. The process of detection of photons by dissociation of silver bromide in a photographic plate leading to a cascade effect that produces the accumulation of millions of atoms of silver is an example of the production of an event. The appearance of a dot in the photographic plate [7]. The dot and its properties have, like any property, a mathematical counterpart in the formalism of quantum mechanics corresponding to projectors in the Hilbert space of the detecting plate. We are thinking in this kind of events as the building blocks of the apparent reality. Both the event —the appearance of a dot— and its properties are characterized by projectors [8]. We shall call essential property the projector that completely characterizes the event and denote it by P_E that is a projector on the Hilbert space of the photographic plate. Let us call P_1, \dots, P_n the projectors in the Hilbert space of the plate that characterize the properties of the dot. As we have shown in [8] the properties of an event satisfy $P_i P_E = P_E$.

When one considers non-local systems like particles in entangled states, whose components occupy different positions

¹ in one of the letters to Max Born Einstein says: “the concepts of physics relate to a real outside world, that is, ideas are established relating to things such as bodies, fields, etc., which claim a ‘real existence’ that is independent of the perceiving subject. ... It is further characteristic of these physical objects that they are thought of as arranged in a space-time continuum. An essential aspect of this arrangement of things in physics is that they lay claim, at a certain time, to an existence independent of one another, provided these objects ‘are situated in different parts of space’. Unless one makes this kind of assumption about the independence of the existence (the ‘being-thus’) of objects which are far apart from one another in space which stems in the first place from everyday thinking - physical thinking in the familiar sense would not be possible.”

in space-time it is not possible to speak of a state at a given time, since that is a notion that depends on the Lorentz reference frame chosen. However, if the state is defined by its disposition to produce events one can rigorously show [9] that such disposition is uniquely defined and the state in the Heisenberg picture only changes when events take place. The disposition to produce events separated spatially in the sense of relativity, that is not causally connected, is independent of the temporal order that one assigns to such events. In fact, the assigned order is purely conventional since it depends on the reference system used. The concept of states in quantum systems is necessarily holistic in space-time [1]. Very far removed from the notion of separability that Einstein considered mandatory in order to do science.

Each primitive concept that is introduced in the axioms of quantum mechanics is associated with a mathematical concept well known in ordinary quantum mechanics, but one can only assign them a well defined philosophical meaning if one has an interpretation of the theory. For example, quantum mechanical events could not be used as the basis of a realistic ontology without a general criterion for the production of events that is independent of measurements. On the other hand, the concepts of state and system only acquire ontological value when the events also have acquired it. It is important to remark that having a realist interpretation of quantum mechanics not only allows us to understand the measurement process; it also allows understanding how a world with uniquely defined properties arises from a quantum world of potentialities. Some of these interpretations will allow us to derive an ontology where objects and events can be considered the building blocks of reality.

Not all realist approaches lead to ontologies novel enough to imply a significant departure from the point of view of classical physics. For example, Bohm's version of quantum mechanics, also known as Bohm's hidden variable theory, which can be considered as an elaboration of de Broglie's pilot wave theory, falls into such category. In Bohm's theory the "quantum mechanical force" constitutes the main difference between the classical and quantum world.

In general, quantum theories with hidden variables can only attribute definite properties to a certain group of physical magnitudes that can be used to describe a system. In fact the very algebraic structure of the quantum formalism [10] implies that one can only assign definite properties to certain subsets of magnitudes called contexts.

The ontology associated with a generic hidden variable theory is therefore not identical to that of a classical theory, where all variables can take values. For instance in Bohmian mechanics only the positions of the particles may take definite values and may be considered fundamental properties from which the other are derived [11]. Bohm's theory postulates an actual configuration that exists even when unobserved.

But the ontology derived from the Bohmian description will only imply relatively minor changes with respect to classical physics. Indeed, the language of classical physics could be used within the chosen context as long as one admits the existence of non-local forces.

The properties are derived, just like in classical physics, and only the positions are fundamental. Bohmian ontology may be considered as an ontology of particles. It is based on the assumption that the only observations we must consider are position observations, if only the positions of instrument pointers. For instance, the de Broglie-Bohm theory deals with spins by considering that they are not a feature of the particle, but rather of the wave-function. As such, the spin only has a definite value once an experimental apparatus is chosen and a position measurement is performed.

III. INTERPRETATIONS THAT ADMIT AN EVENT ONTOLOGY

In what follows we will discuss three interpretations that admit event ontologies. They are the Many Worlds Interpretation, the Modal Interpretation and Montevideo Interpretation. As we will see not all of them lead to the same notion of event. As a consequence the corresponding ontologies will exhibit minor variations depending on what interpretation is considered.

A. Events in the Many Worlds Interpretation

Everett addressed the measurement problem assuming that the wavefunction describes the Universe as a whole, including the observers and that it evolves continuously obeying the Schrödinger equation without any discontinuity or collapse.

In order to explain our observations he assumed that the wave function of an observer would, in effect, bifurcate at each interaction of the observer with a superposed object. The universal wave function would contain branches for every alternative result of the measuring object. Each branch has its own copy of the observer, a copy that perceives one of those alternatives as the outcome. Schrödinger evolution ensures that once formed, the branches do not influence one another. Thus, each branch embarks on a different future, independently of the others.

In order to understand how the branches corresponding to different measurement outcomes become independent and each turn out looking classical one uses today the decoherence theory. For Everett, all elements of a superposition (all “branches”) are “actual”, “none any more real than the rest.” Summarizing: worlds “are mutually dynamically isolated structures instantiated within the quantum state, which are structurally and dynamically quasi-classical” [12]. The existence of possible different “worlds”, is established by decoherence theory.

The ontology of the Many Worlds Interpretation may be considered as a monist perspective where states and events have the same nature. One may consider that in this approach what we call states and events are aspects of a fundamental entity which is the state of the complete multiverse. Notice that the relevant kind of events in the Many Worlds Interpretation corresponds to events associated with observable phenomena that give rise to different “mutually dynamically isolated structures instantiated within the quantum state”.

But one needs to assume that for certain superpositions —that according to decoherence are very similar to statistical mixtures—, the different states that compose the statistical mixture acquire independent reality. The appearance of independent realities in the branching process may be considered as the events. But strictly speaking one does not have statistical mixtures but superpositions, and it is not clear how to assign any reality to these superpositions, given the fact that different basis may be used to define them. It is not our purpose to enter into a critical analysis of the interpretations, however we remark that the ontology itself is problematic in the Many Worlds Interpretation.

B. Events in Modal Interpretations

Van Fraassen [13] proposed an alternative procedure to eliminate the projection postulate from the quantum theory. His proposal relies on the distinction between “dynamical states” and “value states” or “actual-valued” observables. The dynamical state is the usual state of quantum mechanics: it determines which properties may the system have in its future and their corresponding probabilities. The value state represents the physical properties that the system actually has at a given instant. The Modal Interpretation in its different versions assumes that physical systems at all times possess a number of well-defined physical properties, these properties can be represented by the system’s value state. An essential feature of this approach is therefore that a system may have a sharp value of an observable even if the dynamical state is not an eigenstate of that observable. What changes in the different versions of this interpretation is how the actual valued properties are defined.

In the Kochen–Dieks (K-D) Modal Interpretation the biorthogonal (Schmidt) decomposition of the pure quantum state of the system selects the actual-valued observables. In the Vermaas–Dieks (V-D) version the actual-valued observables are defined by the spectral resolution of the system’s reduced state, obtained by partial tracing. Even though these proposals are well suited to describe ideal measurements they failed to describe imperfect measurements. In fact, they do not select the right properties for the apparatus in the imperfect case (see Albert and Loewer [14]).

Castagnino and Lombardi have observed that the Hamiltonian of the quantum system plays a decisive role in the property-assignment rule that selects the observables whose possible values become actual. Once H is given, it is assumed that the actual-valued observables of the system S are H and all the observables commuting with H and having, at least, the same symmetries as H . This is the Modal Hamiltonian Interpretation (MHI). Independently of the particular implementation of the Modal Interpretation adopted one can consider that each time a property is instantiated in a system an event occurs.

As Lombardi and Dieks observe in [15]: “In modal interpretations the event space on which the (preferred) probability measure is defined is a space of possible events, among which only one becomes actual. The fact that the actual event is not singled out by these interpretations is what makes them fundamentally probabilistic. This aspect distinguishes modal interpretations from many-worlds interpretations, where the “probability measure” is defined on a space of events that are all actual. Nevertheless, this does not mean that all modal interpretations agree about the interpretation of probability.” We share the MHI point of view that adopt a possibilist conception, according to which possible events *possibilia* constitute a basic ontological category (see Menzel [16]). The probability measure is in this case seen as a representation of an ontological propensity of a possible quantum event to become actual [17]. The Modal Interpretation does not assume that the state changes after a property instantiates and it assumes that the evolution is always unitary. Nevertheless it is assumed implicitly that after the observation of a property the disposition of the system in its subsequent evolution is the same as the one the system would have had if the state had collapsed. Therefore, the ontology of states and events appear to be well suited to this interpretation. However, here the relevant kind of events corresponds to instantiations of properties both of macroscopic and microscopic systems and therefore they do not necessarily correspond to phenomena.

We have already expressed some reservations about the Many Worlds ontology. In the case of Modal Interpretations, we also have reservations which are related again with some implicit approximations. In this case with the notion of “elemental quantum system”, that introduces an ambiguity in the definition of the “actual valued observables”.

In fact, in order to have a well defined hamiltonian one needs to assume that S is an “elemental quantum system”, that is a system which is in tensor product with the rest of the Universe. Strictly speaking, only the whole Universe may be considered as an elemental quantum system, that is a system that do not interact with its environment, and therefore the MHI is again -as the Many Worlds Interpretation, based in an idealization. In this case the idealization of an isolated system.

C. Events in the Montevideo Interpretation of quantum mechanics

The closest we have to an explanation for the measurement process within the quantum theory is environmental decoherence. It is based on the fact that when a quantum system interacts with an environment with an enormous number of (microscopic) degrees of freedom, the state of the quantum system suffers transitions that *almost* look like the abrupt evolutions one needs to postulate in measurements. However, even if they are difficult to detect, quantum superpositions are still there and may be in principle observed.

Environmental decoherence is important because the measurement processes involve interactions with macroscopic systems with many degrees of freedom. Interactions with the environment were neglected for decades and the relevance of this effect was only recognized in the 1980’s

A new interpretation was recently proposed. The novelty of this interpretation of quantum mechanics is the inclusion in the quantum description of another factor up to now neglected. In the standard Schrödinger description of the evolution, time is treated as a classical external parameter, but time is actually measured by physical clocks that obey quantum mechanical laws. Quantum measurements of time have a limited precision. This limitation arises from quantum fluctuations and gravitational time delay and has a fundamental nature [18]. This effect, first noticed more than 50 years ago has been recently confirmed by many authors. We have shown that a quantum mechanical treatment of time [19] combined with fundamental limitations of measurements stemming from general relativity, lead to a modified Schrödinger evolution that allows transitions between quantum superpositions and statistical mixtures.

When one takes into account the limitations in measurement imposed by quantum mechanics and gravity, the states resulting from decoherence are indistinguishable from those produced by the measurement postulate. The “almost” of the standard approach to decoherence is removed by fundamental limitations predicted by the theory itself and the transitions from superpositions to statistical mixtures required to explain measurements are deduced. This in turn supplies an objective criterion that says when and what events may occur. Events occur when the state of a system resulting from a full quantum mechanical evolution becomes a statistical mixture [8, 20]. The transition of the state of the system plus environment to a statistical mixture gives necessary and sufficient conditions for the occurrence of events. Events are assumed to occur as random choices of the system. They simultaneously lead to the production of events and the state reduction. It is not assumed in this interpretation that these choices are part of a process that the theory describe as it is the case of the Ghirardi–Rimini–Weber approach. It is an additional postulate that however needs no reference to a classical world or a notion of measurement.

The modified evolution induced by the use of a quantum time leads for a quantum system coupled with its environment to a state that is a statistical mixture. This provides an objective criterion for the occurrence of events and state reductions that establishes when events and changes in the state may occur without disrupting the prediction of the evolution equation. It is important to remark that within this interpretation events always occur in systems that include a macroscopic environment and therefore are macroscopic as the phenomena considered by Omnès. In this sense this interpretation keeps more similarities with the Many Worlds Interpretation than with the Modal ones.

Up to now one only has a precise analysis of the complete process leading to the statistical mixture for spinning particles. For other systems one can prove that the state of the microsystem coupled to the environment approaches exponentially to the statistical mixture. We consider that this is enough to assume the indistinguishability. Given the fact that the distinction between an evolution that includes quantum time measurements or a quantum reduction would require an exponentially growing number of individual measurements in order to have the required statistics for distinguishing a non vanishing exponentially small mean value from zero. Limitations referring to the existence of a finite number of physical resources in a finite observable Universe would be enough to ensure undecidability. [20, 21] However, this is a point that needs further study to have a definite answer.

Summarizing, for all the interpretations that admit an event ontology and for quantum systems interacting with a macroscopic environment that has many degrees of freedom, events will be plentiful. They not only occur on measuring devices, they occur around us all the time. Measurements are nothing but the assignment of quantitative properties to events occurring in measuring devices.

IV. EMERGENCE IN TERMS OF AN EVENT ONTOLOGY

Emergent phenomena are said to arise out of and be sustained by more basic phenomena, while at the same time exerting a “top-down” control, constraint, or some other sort of influence upon those very sustaining processes. We are interested in strong emergence, its defining characteristics are qualitative novelty and ontological non-reducibility. The notion of emergence we are proposing considers emergent entities to be genuinely novel features of the world. By definition, one talks here of causal powers that cannot be explained in terms of the micro causal powers but arise from the existence of certain macro level entities.

Strong emergence seems to be particularly relevant: if someone attempts to explain natural phenomena without denying the existence of mental processes in physical terms she must demonstrate the viability of emergence with downward causation. The central point which this concept refers to is that higher level mental events have the ability to influence the behavior of more basic levels. This requires philosophical compromises that are not easy to justify in terms of an ontology based on classical physics. In fact attempts of explanation within a mechanistic view are problematic. As was proposed by Sperry [22] and observed by McLaughlin [23], emergence in the context of Newtonian Mechanics needs to postulate different ad hoc, basic, configurational force laws exerted by complex structures of particles that dominate on the standard microscopic fundamental forces exerted by pairs of particles in order to explain emergent phenomena. This should require a kind of “intelligent design” for any emergent system from a molecule to a living being incompatible with any scientific explanation. Attempts to understand emergence from classical physics are destined to fail and have led those that followed this path to believe, like Bedau does [24] that “strong emergence starts when scientific explanation ends.”

We will show that certain quantum mechanical systems present precisely this kind of top-down control. It is well known that in quantum theory the physical state of a system of particles cannot always be reduced to the state of its component particles, “or to those [states] of its parts together with their spatiotemporal relations, even when the parts inhabit distinct regions of space.” as noted by Maudlin [25]. We want to emphasize here that this quantum mechanical holism involves systems that have ontologically new properties and present downward causation where macro-systems have effects on their micro components [26].

The traditional objections to emergence result from the explicit or implicit use of ontological concepts based on classical physics and are not tenable when assessed from a quantum mechanical ontology of events.

A. Ontologically new properties

Let us start by showing that quantum systems may have ontologically new properties. Quantum systems may have certain quantum states, called entangled, that have well defined properties that neither follow from the properties of parts, nor from relations among them. To understand this statement better, let us review how entangled states are defined and contrast them with systems in classical states.

In classical physics the state of a system of particles $(\vec{r}_1, \vec{v}_1, \dots, \vec{r}_N, \vec{v}_N)$ is simply the union of the states of each particle. Its knowledge determine all the properties of the system. For instance the energy $E(\vec{r}_1, \vec{v}_1, \dots, \vec{r}_N, \vec{v}_N)$. All the properties of a classical system are functions of the properties of its components.

In quantum mechanics things are very different. Most of the properties of a system do not have well defined values until measured; for instance the position of an electron is not well defined until a dot is produced in the photographic plate and it is detected. However any quantum system in a pure state has some well defined properties. For instance, a spinning particle can take two possible values of its component along an axis \hat{z} : up or down. When one performs repeated measurements on particles on a given state one observes dots appearing in the upper region with certain probability and in the lower with the complementary probability. When the electron is in a state that leads with certainty to a dot in the upper region of the detector identified by $z > 0$, one may say that it is in the state $|z, \text{up}\rangle$. In this case one may assign the property “z up” to the state. This is the only property that one can assign to this state. The measurement of any other component will not lead to a unique value: i.e. always up or always down. In general, the properties of a pure state $|\psi\rangle$ is always associated with a set of projectors $P_1 \dots P_N$ such that $P_i |\psi\rangle = |\psi\rangle$. It is only when one knows with certainty what will be the behavior of the system in certain state that one may assign it a property. In fact, as we have observed before, events have many well defined properties but typically states do not have properties until they produce events. One may assign properties to states only indirectly through the properties observed in some events produced during the preparation process of the state.

Systems composed of several particles may also have states with some properties with well-defined values. However, these properties may refer to the system as a whole and, in these systems, there may not be any property for the states of individual particles with well-defined values. These composite systems are called entangled. More in general, entangled systems are those that have properties with well defined values than cannot be inferred from those of their

constituent parts. As we will see in what follows, it might even be the case that the constituent parts have no well defined properties and yet the system as a whole does.

Consider two electrons with spin in the z direction in a state

$$|\psi_0\rangle = \frac{1}{\sqrt{2}}|1, z, \text{up}\rangle|2, z, \text{down}\rangle + \frac{1}{\sqrt{2}}|1, z, \text{down}\rangle|2, z, \text{up}\rangle. \quad (1)$$

Neither the state of particle 1 nor the one of particle 2 have well defined properties. No matter what component of the spin of one of the particles one measures, one has a probability $1/2$ of measuring up and $1/2$ of obtaining down. Even though each entangled electron do not have well defined properties for their spin components the total system does. For instance one can show that it has total spin $s = 1$ in Planck units, and z component of the total spin $s_z = 0$. It is only when the observations made on particle 1 and 2 are compared that one can discover the properties of the total system. One could also determine these properties when the complete system is measured. The constituents therefore now form an inseparable unit endowed with properties without the individual systems having any property —any spin component— with well defined value.

This holistic behavior is actually not an exception but is the generic behavior of two quantum systems after an interaction. For instance, the precise vibrational modes of a molecule depend on the entangled system of electrons and nuclei. Underlying this feature is the exponential growth of states with the number of component particles in quantum mechanics in contraposition with the linear growth in classical physics. Most of these states and their corresponding properties —projectors— would have never occurred in systems with independent —non entangled— components.

Ontological novelty manifests itself in the emergence of new properties that do not result from properties of the parts. They arise only when the composite structure is constituted.

The emergent properties of such systems are crucial for explaining chemical or biological properties in physical terms. For instance: the magnetic counterpart of the properties of entangled spins work as a magnetic needle that is at the basis of navigational skills of the European robin, a migratory bird able to detect the direction and strength of the Earth magnetic field. A “sixth” sense known as magnetoreception [27].

The philosopher of science Paul Teller was the first in noticing that quantum phenomena show relations that do not stem from non-relational properties of their relata, as is characteristic of the classical description of the world. However, the ontological meaning of his observation, in particular its implications concerning the problem of emergence, could not be elucidated because he could not discard a purely instrumentalist interpretation and his use of the notion of property is still reminiscent of classical physics. Entangled systems present what Teller calls: relational holism [28]. The emergence of new properties of the whole in a quantum world where events and properties play a fundamental role is the crucial manifestation of ontological novelty.

Healey [29] has introduced the notion of Physical Property Holism that assumes that there are physical objects “not all of whose qualitative intrinsic physical properties and relations supervene on qualitative intrinsic physical properties and relations in the supervenience basis of their basic physical parts.” He observed that the existence of physical property holism in entangled systems depends on the interpretation of quantum mechanics that one adopts. Our discussion was restricted to the ontology of events and it is in this context that have proved that ontologically new properties arise.

B. Downward causation

A strong form of emergence also requires downward causation, namely, the emergence of novel causal powers. Here a double goal arises: to characterize such form of causality in physical terms and to show that at least certain systems, like the quantum ones, exhibit downward causation.

A notion of causality that is suitable to the ontology of states and events has been developed by Chakravartty [30]. He finds his notion on what he calls “causal properties”. As we have associated the notion of property to projectors in the Hilbert space we prefer to speak about causal powers. Following Chakravartty we will recognize a causal power for its capacity to confer dispositions on the objects that have them to behave in certain ways when in the presence or absence of other objects with causal powers of their own. This dispositional idea of causality —originally due to Heisenberg— is the one we have adopted in our work for states: recall that quantum states characterizes dispositions to produce events in their interaction with other systems.

An object will present downward causation if the parts have some behaviors that are dictated by the state of the whole and that cannot be predicted from the knowledge of the state of the parts. The previous example of an entangled state shows that in quantum mechanics there is state non-separability [29]. In the example of entangled spinning particles the states of the parts are represented by reduced density matrices and they are just a statistical mixture of “up” components and “down” components while the complete entangled state has more information, in particular information about correlation between the events observed in each component. For instance the spin

measurements of both particles will be correlated. Whenever both observers measure the spin in the same direction their results would be opposite, —up for Alice and down for Bob or vice versa—. The observers could never have figured out these correlations by looking at the individual systems in isolation without comparing their measurements. The complete system has certain non locality such that when one electron chose to answer up, the other necessarily needs to chose down. Such correlation does not involve time. As it is well known Bell’s theorem establishes that it is not possible to explain this kind of behavior assuming that each part follows a pre-established set of instructions, in other words, assuming that each part has some local hidden information telling it how to act before each measurement. In other terms the state of the entangled pair of particles given for instance by $|s = 1, s_z = 0\rangle$ is not mathematically determined by the the states of the parts. In fact there are two states $|s = 1, s_z = 0\rangle$ and $|s = 0, s_z = 0\rangle$ whose parts are in identical states.

These correlation are generic for any entangled state. Any system in an entangled state presents downward causation. The events produced by different components of the system have correlations that do not result from the states of the parts. In fact, the very characterization of the entanglement of a pure state in terms of the Von Neumann entropy or entanglement entropy that is always a positive quantity shows that the complete information required for the determination of the whole cannot be recovered from the information of the parts or that the state of the whole cannot be mathematically expressed in terms of the states of its parts.

Less trivial explicit examples of downward causation may be found in the molecular behavior where entanglement cannot be ignored or in quantum computers. In quantum chemistry calculations, entanglement is related with the correlation energy. This energy is neglected in Hartree Fock calculations and the energy error of the Hartree–Fock approximation to the wavefunctions of a molecular system is a measure of the effects of downward causation in the behavior of the molecular components. For instance, it is downward causation of the whole molecular system state that determines the precise vibrational behavior of the nuclei.

For quantum computers, the existence of quantum correlations in the entangled states between different input and output outcomes is at the basis of the application of quantum algorithm that allow to solve certain problems like integer factorization using Shor’s algorithm much more quickly than any classical computers. The disposition of the quantum computer to produce the correct correlation between the input and output results at the end of the computation is the manifestation of the quantum downward causation that is at the basis of the improvement of the computational capabilities of quantum computer.

We have characterized the downward causation of a system by its disposition to produce certain effects that is not present in the dispositions of its parts. This kind of disposition is the characteristic feature of systems in entangled states. In turn, the existence of entangled states in quantum systems result from the exponential growth of Hilbert spaces of composed systems in opposition to the linear growth of the states in classical physics. At the basis of the novelty and non-reducibility of emergent systems it is this exponential growth in the possible behaviors of the quantum systems whose philosophical implications can be recognized when the appropriate ontology is put into action.

Notice that this kind of emergence admits a reductionist explanation in the sense that one can in principle explain the dynamics of the compound quantum mechanical system in terms of the dynamics of the components considered in isolation and their interactions and describe the Hamiltonian evolution leading from the isolated components to the entangled system. Hüttemann [31] has called this description diachronic micro-explanation. Summarizing, emergence is not the exception but the rule in interacting quantum systems, its so natural that it usually remains unnoticed. Strong emergence manifest itself in most complex systems, it is a natural result of the interaction of quantum objects.

The recent advances in the understanding of the role of quantum mechanics in biology [32] and the previous analysis of strong emergence in quantum mechanics rise the expectations of understanding mental phenomena and their causal powers in physical terms. The issue of emergence, also known as non reductive physicalism in the context of studies of the mind brain problem, has been extensively analyzed mostly using notions of supervenience that assume some form of separability and are not valid in quantum mechanics as shown by Maudlin [1]. We consider that in quantum entangled systems with downward causation and dispositional states that leads to probabilistic outcomes the issue of free will may be posed in a clear explicit way and will be analyzed elsewhere.

V. SUMMARY

Several interpretations of quantum mechanics admit event ontologies. These realistic interpretations lead to an important revision of the notion of matter and its potentialities. Systems of particles in entangled states have new behaviors and emergent properties.

The quantum theory implies that the lower levels are modified even up to the point where they lose part of their individuality when they integrate into an entangled system in a higher level of the hierarchy. The emergent structure has novel properties and downward causation. Interpretations of quantum mechanics that admit an event ontology solve the traditional problem of explaining emergence.

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