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Quantum mechanics: ontology and information

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Abstract

Quantum theory shows that natural laws cannot be understood as ruling single events since the latter occur randomly. Nevertheless, the physical world shows everywhere order whose source cannot be represented by the latter. It is shown that this order is due to the presence of quantum correlations. Since their effect is to reduce the space of the possible events, they can be considered as causal factors. However, being correlations, they do not display the dynamic character that would be required in order to produce a determinate effect. This is why they need additional local factors in order to concur to the production of a certain event. If not so, this would even imply a violation of Einstein's locality since correlations could be used by themselves to transmit superluminal signals. Due to such a character of correlation, they can be understood as kind of potential reality needing actual (and local) context to be effective. This allows also a distinction that is classically unknown between locality and globality. Such a distinction solves the important problem of measurement showing that ultimately we have irreversible local processes while globally everything is still reversible. In particular, it is a shift of information that can explain this local phenomenon. In fact, quantum systems are essentially information and also the measurement process is ultimately a dealing with information: information processing (preparing a system), information sharing (coupling a system with an apparatus) and information selection (detecting). State, observable and property appear as equivalence classes of these three procedures, respectively. Finally, the distinction between interpreted and uninterpreted ontology is considered in a Kantian perspective, but it is also shown that the approach supported here is rather a critical realism.

1. Random events

The most revolutionary aspect of quantum theory is the acknowledgment that in the physical world there is an irreducible randomness [4]. In other words, there is no law allowing us to predict certain events with certainty. We may compare this astonishing result with the idea that the majority of physicists had at the end of the 19th century about the power of classical laws. It is indeed well known that Lord Kelvin, in his 1900 address to the British Association for the Advancement of Sciences, seemed to assume that physics was essentially accomplished as a scientific discipline, since he affirmed that "there is nothing new to be discovered in physics now. All that remains is more and more precise measurements". What Lord Kelvin meant was that classical laws covered potentially every phenomenon and that everything could be in principle perfectly measured, so that our ability to determine with exactitude any physical phenomenon was only an issue of technical power.

Two examples will clarify the difference between the classical and quantum-mechanical approach [4]. Consider an apparatus known as a Mach-Zehnder interferometer. The incoming beam of light (that is pumped by a laser) is split (by a first beam splitter) into two components along two main paths and then (by a second beam splitter) these components are recombined and sent to the final detectors (two, in the basic arrangement). Until the second beam splitter the description could be to a certain extent in accordance with classical laws, since the light behaves wave-like and produces typical interference phenomena in accordance with classical predictions. However, when impinging the detectors, the beam seems composed of small particles (photons) since we have discrete clicks. Moreover, we can arrange the apparatus in such a way that a single photon can be sent at a time through the first beam splitter. In this case, we have a phenomenon that is fully unknown classically: the photon makes interference with itself, which means that we have no longer a superposition of distinct waves but a new, classically unknown state of superposition of the two possible final detection events. Precisely this circumstance determines the randomness of those events.

Consider now a different experimental context: a beam of light prepared in a polarization state, say with light oscillating along the 45° direction. Suppose that we set a polarization filter along the vertical direction. Classically, we would expect that the beam will behave uniformly across time, since any classical system or object prepared in the same state (polarization at 45 degrees) and subjected to the same experimental conditions (vertical filter) behave in the same way (produces the same outcome). This is also what seems to happen since we see that the beam will uniformly pass the filter with a reduced intensity (by one half). However, when we perform a finer analysis thanks to quantum mechanics, we shall discover that the beam can be understood as “composed” of photons each of which in a superposition state of vertical and horizontal polarization. In such a state, *each* of them has a probability of one half to pass the filter or be blocked by it, what implies that in the mean one half will pass the test and the other half will be blocked. This is quite extraordinary, since it means that systems prepared in the same state will behave differently. Moreover, since they have been prepared in the same state and there is therefore nothing that allows us to discriminate among them, we cannot predict which singular photon will pass the test and which not. This is why we have irreducible events when dealing with quantum-mechanical systems.

This situation determines a new understanding of the relations between events and laws as well as of the issue of causal relations. I shall deal with the latter issue below and focus here on the relation between laws and events [6]. According to the classical view as expressed by the words of Lord Kelvin quoted above, natural laws are thought to rule single events and properties. At the opposite side, if we take the above quantum-mechanical description seriously, we are obliged to admit that any law will at most allow us to predict, at a general level, the behavior of quantum systems but not what a quantum system will do at a particular or individual level. Indeed, we can say that half of the photons will pass the test represented by a vertical polarization filter but we cannot predict which one will do it. In other words, laws have only a general significance. Here we need to immediately overcome a possible misunderstanding. We could interpret this situation as meaning that quantum laws have a statistical character as it happens for statistical mechanics. There is a long and honored tradition that considered this to be the case [4]. However, subsequent experimental tests have clearly shown that quantum laws are as deterministic as classical ones are but that they rule the *general features of any single* system and not the particular behavior that it will assume. Indeed, the so-called Schrödinger equation [4] rules the probability amplitudes (whose square moduli allow us to compute the relative probabilities) to get certain experimental outcomes when the object system undergoes determinate experimental procedures (preparation and premeasurement). In the case of the interferometry experiment above, the Schrödinger equation will tell us the probability of a single photon to be detected by a certain detector but will not ensure us that it will in fact impinge the latter. In other words, quantum systems are intrinsically probabilistic, which means that probability does not represent (as it is the case for classical mechanics) a subjective ignorance of the actual state of a system but expresses an objective uncertainty affecting the system.

2. Correlations and information

A world ruled only by chance events could never produce any kind of order or regularity. More specifically, reality would consist of unrelated pieces of matter and any connection or relation would simply be an illusion or addiction of the mind. Should the world be a random collection of particles in Brownian motion, whose sizes, masses, speed, and so on are totally arbitrary, my guess is that no single configuration of things would emerge at all. Indeed, as soon as one ordered configuration could form by chance, it would be rapidly destroyed by the random motion of the other particles and following interactions [6]. It is well known that L. Boltzmann accounted for the macroscopic phenomenon of gas pressure in terms of the random motion of the gas molecules. This could be interpreted in the sense that a pure random motion could give rise to some sort of ordered effects (and macroscopic property). However, without confining those particles into a closed space, e.g. in a piston, such an effect would never be produced. This shows that, without a confining constraint, the disordered motion alone would again be insufficient for producing any ordered effect.

As a matter of fact, we observe order everywhere in our universe. Moreover, quantum-mechanical laws allow probabilistic predictions, which imply a certain regularity. Since probability amplitudes evolve deterministically, we are also able to compute probabilities at later stages of the dynamic evolution of a system if the initial state is known. So, the question is: how is this order generated if the world consists in quantum random events? The problem here is also the solution. When the state of a quantum system changes and therefore the probabilities of obtaining certain events also change, a prediction about the latter would be strictly impossible if the probability amplitudes computable at any moment were independent of each other. This is not the case because, as a manifestation of superposition, in the state of any quantum system, constraining correlations relating all probability amplitudes are somehow nested, thus allowing us to formulate deterministic predictions about all outcome probabilities. In a recent paper [5], I have called such interdependences quantum "features" because they are those characters of the system that, not being properties in themselves, nevertheless determine the probabilities to get certain outcomes and therefore to assign properties to a system. Indeed, true properties are local by definition, while features, being interconnections among components of the system, are non-local by their very nature.

Let us consider the following example: suppose that the state of two particles is a singlet state. In such a case, they show a spin-correlation such that when one of the two particles is found to be in a spin-up state along an experimentally chosen direction, the other one will be necessarily in a spin-down state along the same direction and vice versa. In other words, we expect to obtain either up-down or down-up but never up-up or down-down. If the world consisted of random events only, we would expect to obtain any of these four possible outcomes with equiprobability. The fact that we can obtain only two (either up-down or down-up) out of four cases represents a reduction of the space of possible events. In other words, quantum mechanical correlations act as constraints limiting the space of what we can obtain. For the example of the singlet state such correlations are called *entanglement*. Entanglement is a correlation among several subsystems. However, also correlations in a single system can show this behavior. For instance, in a Mach-Zehnder interferometry experiment, if we choose the relative phase between the two components to be either 0 or 180 one of the two detectors never clicks, which is due to the self-interference of the photon. However, if we block one of the two paths both detectors can click.

3. Information

There is a natural question that now arises: what is the kind of reality that the correlations in our universe consist of? We indeed live in a world that is physical, but correlations are by definition formal [7]. The problem is that correlations and ordinary physical quantities are tightly connected: it suffices to say that correlations are instantiated in physical systems and enter into interactions involving exchanges of physical magnitudes. Now, how is it possible to put together something formal with something else that is not? We need a sort of quantity that is both formal and nevertheless linked to the material dimension. Let us come back to the example of entanglement that we have proposed above. We have shown that, in an entangled state, the outcome statistics are more ordered (two out of four possible cases) than when there is no entanglement (four out of four cases). There is a language for dealing in the most general way with such kinds of problems: the language of information. Indeed, information (and its connected quantity, the so-called Shannon entropy):

- Is concerned with the issue of singling out a subset of elements (the message or the information we like to acquire) from a larger set (the set of all possible messages or at least the set of elementary units out of which any message can be composed, like the alphabet);
- Measures the unlikeliness of performing such an extrapolation, which is expressed by the probability that the latter does not occur or is not chosen. Obviously, if there is no (syntactical) order among the units and the sequence of the latter is random, to acquire or to guess the right message will be much more difficult than in the case in which there is some rule (for instance, in some cases, we can understand that an encrypted message represents an English sentence because of the higher or lower frequency of some letters).

Therefore, we may say that information and entropy are concerned with the amount of order and disorder of a system. The more correlations there are in a system, the more the system is to be considered ordered and the easier the guess is about its state. Indeed, the way in which entanglement can be mathematically described is with the so-called mutual information, that is, the information shared by several systems or components of a system that makes them interdependent.

4. Potentiality and information

An important concept is the following: entanglement is an information resource (consisting in mutual information) called ebit that rather displays potential characters. Indeed, when two particles are entangled we can exchange information in ways that are not allowed in any classical protocol although we need an additional classical resource for doing this. This exchange is called teleportation: if two partners conventionally called Alice and Bob have each a particle of an entangled pair, and if Alice desires to communicate to Bob a bit of information represented by a third particle, she lets her entangled particle interact with the latter and classically communicates the result to Bob, who is now able to recover the information contained in the third particle in the state of his own entangled particle [4]. This shows that an ebit is a potential information resource that can be made effective or active at a later time when some experimental conditions and a classical information transmission are also present.

Potentiality is a concept that has been much devaluated in modern times. Among the reasons of this devaluation there is the assumption that potential realities are a sort of ontological genus different from actual realities. In fact, potentiality only consists in the relation that a certain actual thing entertains with certain contexts or possible actions. It makes perfect sense, even in classical physics, to say that a certain disposition of trees in a forest canalizes the action of the wind in a forest. What is active here is the wind as a physical agent.

Nevertheless, such an effect (wind canalization along a certain direction) would have never happened without such a disposition of trees. Therefore, although such a disposition is perfectly actual in itself, its capacity to concur to a certain action (canalization of the wind) can be said to be only potential to the extent to which it cannot happen (be made actually active) without the wind being itself active. Obviously, the concept of potentiality is not very interesting when dealing with classical-mechanical idealized systems but is far more interesting when dealing with quantum-mechanical systems, as it was clear to Heisenberg, but also with complex realities like living beings [6].

The interesting point now is that quantum mechanics sets very precise bonds on information exchange and therefore on causal interconnections (since we can speak of causal relation only when at least a signal is exchanged). Although quantum-mechanical systems violate the so-called Bell inequalities, which set classical-mechanical limits on information exchange, they do not violate Einstein locality (they do not allow for superluminal or even instantaneous information exchange). Actually, the classical-mechanical limits forbid the kind of interdependencies that are characteristic of quantum entanglement (they assume that physical systems need to be considered either as causally connected, in the sense of efficient or mechanical causation, or as separated). However, quantum mechanics sets a bound that is stricter than Einsteins locality. This is called Tsirelson bound. The reason why it is so was unknown until recent times: it was shown that this bound must be satisfied in order to do not violate the principle of information causality that tells us that we cannot acquire more information than it was actually sent. What is the deep meaning of this principle that to many can sound obvious? The meaning is that quantum correlations (entanglement) are among possible events and therefore outcomes of a measurement procedure. At the opposite side, if the Tsireslon bond were violated, we would have an interdependency, not among events, but among experimental settings or premeasurement procedures [7]. In such a case, we would be able to guess the whole code used by the sender even if it was not sent to us, violating in this way the principle of information causality. This point allows us to define information in all its generality as a relation among possible events,[1] which also explains its potential character when not actually acquired.

5. Causality

Therefore, quantum mechanics does not violate at all the requirements of classical causality. However, it suggests the necessity to deeply reconsider the issue of causality since there are situations in which there is a causal contribution of factors (like entanglement) that are not local by definition, whilst efficient causality need to be always local (implying actually exchange of dynamical physical magnitudes like energy or momentum).

My first suggestion would be to consider quantum systems as instantiating essentially infor-

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[1] First suggested by A. Zeilinger, personal communication.

mation [4]. I am fully aware that we cannot reduce a system like an atom or an electron to information only, since here also other quantities like mass, energy, spin and so on are relevant. I am also aware that many of these quantities do not present the typical characters of information codification and that information is a non-dimensional quantity. However, my modest suggestion would be the following: to consider all the relevant physical quantities as crucial when quantum systems interact (showing dynamical and efficient-causality features) and much less when quantum systems are considered in their isolation or as simply correlated but not as actually interacting. My guess is that, in such a case, information is a more basic quantity (and the definition of information in terms of relation among possible events perfectly describes this situation). This would help us to explain the issue of causality. Indeed, if we admit that quantum systems represent informational resources that are not necessarily active or accessible (I recall that the whole potential information contained in a quantum system is never accessible as such), then they represent possible sources from which we can extract information at a later time when certain experimental or spontaneous contexts are activated. They can then be conceived as the sources of the whole information that is present in our universe but not necessarily as efficient causes of any information acquisition.

One of the biggest misunderstandings brought by some interpretations of the theory of information communication is that information propagates causally as it would be a kind of medium or substance. Actually, information never propagates in this sense and we can never say that a certain source causes certain information to be received elsewhere. This can only be a metaphoric way of speaking but does not describe how things go on. Actually, an information source only need to be a source of variety and not an already preselected message that need to be transmitted as a kind of momentum or energy. Actually, what currently happens when information is exchanged is that any initial potential information is never acquired in its totality, since additional factors at the reception are relevant to this acquisition.

Therefore, I think that we should consider quantum information (and correlations) as a kind of *formal cause* that, when certain actual experimental conditions are made active, can concur to give rise to certain effects. With the term *formal cause* I mean a kind of constraint able to canalize certain dynamical processes (and therefore they are only potential, according to what has been said before). Also *formal causes* were dismissed in modern ages. However, today, when we deal with network theory – and every time we deal with sufficiently complex contexts – we need to take advantage of the notion of constraints [3]. This examination also shows that it is likely that there are two main ways to deal with information at a very basic level: either when we share it, or when we select it (during actual information acquiring) apart from information processing. The crucial point is that such a selection only happens when the receiver receives in fact information and not when this information is at the source or is only shared. To understand this, let us consider "the measurement process."

6. Dynamics and measurement

Quantum systems, when considered in their isolation, show potential features, but when they interact they give rise to actual events. We may take measurement as a model of dynamics from which extracting some general notions. When we measure a quantum system, we do it along three major steps [7]:

- First, we prepare the system in a certain state. This is necessary, since quantum systems are very elusive and we are not able even to start a measurement procedure if we are not able to ensure that the system is ready to undergo certain further operations.
- Then we pre-measure the system: we couple (entangle) it with a certain apparatus (setting). In this way, we select a specific experimental context and therefore single out a certain observable that we wish to measure. Until this step, measurement is fully reversible and we only have determined certain information sharing between the object system and the apparatus.
- The third step is the measurement properly or strictly understood, i.e. detection, an act of information selection since we single out (in a way that is not controllable, as previously explained) a single outcome among many possible ones. It is here that we assign an actual property (like to be localized in one of the two paths of an interferometer) to the system.

What is important here is that the whole dynamics establishes a sort of trade-off between potential and actual aspects (if any) of quantum systems. Therefore, dynamics has a sort of ontological primacy in quantum mechanics.

Another important issue is the following: although very elementary, quantum systems show a certain shift along their dynamical evolution. In other words, when cycling along a certain circuit they never go back precisely to the same state. This phenomenon is called geometric phase.

7. Global and local

The reader may be astonished by the fact that during the measurement we start with a quantum system showing a certain potentiality and end with certain actual events. How is it possible? This appears even more puzzling because, if we assume that a quantum system has been prepared (as it is often the case) in a certain superposition of possible measurement outcomes, to get a single outcome out of that superposition would violate the laws of quantum dynamics (the Schrödinger equation), which are linear and therefore forbid such a result. The solution of this problem is to consider that quantum systems are open to the environment. Therefore, when we measure them, most of the information (which consists, as previously stressed, in a relation among possible outcomes) goes lost into the environment while we get only a single outcome. This is even necessary, since such correlations can never be acquired or measured as such. This phenomenon is called *decoherence* and essentially tells us that the apparent violation of quantum dynamics only happens from our local perspective [4].

However, when we consider the global evolution of the whole universe, this still happens in perfect accordance with quantum-mechanical laws. Therefore, the apparent local violation is only due to a local shift in the amount of order and disorder. Indeed, entanglement (and mutual information) is a source of order and in fact most entangled systems show a zero-entropy state (maximal order). However, to locally get a single outcome means a sort of ”break” of this order (the result is a far less ordered state). Therefore, in the local context of measurement, entropy (and disorder) grows. However, if the amount of order of quantum systems is conserved (due to the necessity to preserve linearity), this means that local measurements (or measurement-like interactions) “free” the source of order that could be used elsewhere in our universe, contributing to explain the puzzling circumstance by which, although the world is ruled by the second law of thermodynamics, it shows creation and re-creation of order everywhere and at every scale [6].

The distinction (but also the entrenchment) between local and global is typical of quantum mechanics and could be very fruitful for further scientific enquiry.

8. State-observable-property

As I have pointed out, a state can be prepared in the first step of measurement. Since different procedures can lead to the preparation of the same state, it is suitable to operationally consider the state as an equivalence class of preparations [5]. Since different premeasurements can lead to a later measurement of the same observable, we can define an observable as an equivalence class of premeasurements. Finally, since different detections can lead to the attribution of the same property, a property can be considered as an equivalence class of detection events. Let us consider the latter point a little: any event is in itself a pure happening. It tells nothing about any system whatsoever. It is only thanks to the coupling with the objective system (and therefore thanks to the previous two steps of the measurement process) that we are able to make such an assignment.

This shows that a property (and also a state or an observable), although grounded in some ontological reality, is not itself an ontological reality (being an equivalence class). It is something that we are allowed to attribute given certain conditions. To misunderstand properties (as well as states and observables) as ontological realities is one of the major flaws of classical mechanics.

Let us call state, observable and property as pieces of an interpreted ontology (that is, interpreted thanks to a theory: quantum mechanics). Then, the question naturally arises:

which is the ontological substrate of these classes? We have implicitly already mentioned it: correlations, events, and their dynamic interplay [1]. Let us call these "objects" pieces of an uninterpreted ontology.

The distinction between interpreted and uninterpreted ontology is somehow reminiscent of the Kantian distinction between phenomenal knowledge, on the one hand, and world (or thing) in itself, on the other, or at least I tried to take into account this lesson. However, there is also a fundamental distinction. According to Kant, any form is due the productive faculty of the subject and is therefore imposed on a reality that is perceived from the start into the framework of such forms. For this reason, we can say nothing about it as such. At the opposite, I assume that we interact with an independent reality that has the power to correct our hypotheses and therefore allows us also to formulate moderate guesses about its character in itself. In such a sense, the forms are not only due to the activity of the subject, but are the result of such an interaction. This is why we can make distinctions (like between events and correlations as pieces of uninterpreted ontology) that would be certainly impossible on pure Kantian basis. Unfortunately, the transformation of Kant's important insight about the subject as source of productive activity into the sole source of activity has given rise, as well known, to the idealistic approach. At the opposite, from an ontological point of view, I support here a weak form of realism (acknowledging potential reality and formal causes) as well as, from an epistemological point of view, a critical or fallibilist realism (our knowledge is not a mirror of reality but reality corrects our hypotheses). On the latter point, I am rather a follower of Peirce's philosophy [7]

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