The Ontology of Events: Bohmian Mechanics versus GRW Theory

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1. INTRODUCTION

Quantum mechanics is plagued by several problems of interpretation about what it says about the world. The debate about quantum mechanics is mainly linked to two fundamental matters: the interpretation about atomic and subatomic processes and the measurement processes, namely the objectivation of macroscopic properties. In this regard, since the birth of quantum theory, a schism in physics, the formation of two opposed arrays developed. On one side, the founders of quantum mechanics, i.e. the orthodox party, the exponents of Copenhagen and Gottinga schools (Bohr, Heisenberg, Born) believed that in the description of atomic processes we must ascribe a special role to the observer and that it is not possible to provide a causal description of atomic phenomena. On the other side, renowned physicists such as Einstein, Planck, Schrödinger, de Broglie – i.e. the dissentients – did not accept the acausal interpretation of quantum mechanics (Fiscaletti 2003 and 2007).

The founders of quantum theory handed on to us a set of ideas known as standard interpretation of quantum mechanics. The standard interpretation of quantum mechanics establishes that Schrödinger equation (the fundamental equation of motion of microscopic systems) cannot be used in order to explain the results of measurement processes. This equation implies in fact that, when a measurement is performed on a system which at the beginning is in a superposition state, then after measurement one should obtain a superposition of different results of the measured quantity (and thus of distinguishable macroscopic situations). In order to reproduce the fact that in measurement processes one always obtains a well defined result, the standard version of quantum mechanics introduces an element known as reduction principle of the wave function. This principle establishes that when a measurement is performed on a system which at the beginning is in a superposition of macroscopically different states, then after the measurement its wave function collapses into one of these states. This final state is not predictable with certainty but only probabilistically. Moreover, according to the standard version, the reduction of wave function is caused by the observer.

The philosophy of standard quantum mechanics can be so synthesized in the following Bohr's sentences: "A phenomenon is not a phenomenon until it is observed" and "It is a mistake to think that physics' aim is to find how nature is. Physics concerns what we can say about nature" (Bohr 1961). Bohr thought therefore that in quantum mechanics the observer does not reveal the phenomenon but somehow fixes and defines it.

According to Bohr, the observer plays an active role in the study of the behaviour of elementary particles, in other words the observer influences the experimental results regarding atomic and subatomic processes.

Einstein and the dissentients thought instead that the description of quantum phenomena proposed by Bohr and by the other physicists of Copenaghen and Gottinga schools, despite functioned well in the prediction of experimental results, was not complete. Einstein believed that the standard quantum mechanics developed by Copenaghen and Gottinga schools was not a perfect theory and that it could be made causal by introducing some additional parameters. Einstein's point of view was thus that the behaviour of subatomic particles is independent from the observer, that it depends on some "hidden variables" besides their wave functions.

As regards the debate on the foundations of quantum mechanics, the clash between orthodoxes and dissentients did not find solution and continues today in a very lively way. Despite the majority of physicists think that the debate between Einstein and Bohr, lasted many years, was won by Bohr, today we can affirm with certainty that it has been solved in favour of Einstein. What Einstein wished and Bohr thought impossible exists. A quantum mechanics without the observer exists, in which measurement processes can be analysed in terms of more fundamental concepts.

Today we have got some significant versions of quantum mechanics which do not ascribe a special role to the observer: they demonstrate that Bohr's interpretation of quantum processes cannot be considered convincing and satisfactory, both from the physical and from the philosophical point of view. In this regard, bohmian mechanics and GRW theory assume a particular importance. Bohmian mechanics, known also as de Broglie-Bohm pilot wave theory, describes a world in which subatomic particles move along well defined trajectories in agreement with a law of motion determined by the wave function. Bohm's version of quantum mechanics allows us to describe atomic and subatomic processes without ascribing a crucial role to the observer and to recover some causality also in the microscopic world. GRW theory, so called from the names of its three authors, the Italian physicists Ghirardi, Rimini and Weber, solves the quantum problem of measurement starting from the idea that subatomic particles occasionally, in virtue of fundamental physical laws, undergo processes of spontaneous localization. Each of these two approaches can be seen as an answer to the problem of formulating a quantum mechanics without the observer and as a realization of Einstein's intuition that standard quantum mechanics does not provide a satisfactory representation of physical reality and of his idea that a better theory is possible. If we base ourselves on Bohmian mechanics and GRW theory, Einstein's view can be considered more convincing than Bohr's interpretation. The aim of this article is just to provide a general framework about the ontology of events which can be derived from Bohmian mechanics and GRW theory.

2. Bohmian mechanics and the ontology of particles

Bohmian mechanics, know also as de Broglie-Bohm pilot wave theory, represents the most significant and satisfactory hidden variables theory predictably equivalent to quantum mechanics, able to give a causal completion to quantum mechanics. It is included inside that important research stream directed to complete standard quantum theory in a deterministic sense.

This theory is based on two fundamental starting-hypotheses. Before all, the idea that quantum mechanics is not complete and must be completed by adding supplementary parameters to the formalism, the so called hidden variables. The hidden variables of the model are the positions of all the particles constituting the physical system into examination. The first starting hypothesis of Bohm's pilot wave theory is just this: our physical system is prepared in such a way that, at the initial time t=0, it is associated with a specific wave function $\psi(\vec{x},0)$ which is assumed to be known perfectly, and moreover is in a point $\vec{x}$ (among those compatible with the function into examination) that instead we ignore (it is in this sense that the position is the hidden variable of this theory).

The second starting-hypothesis of Bohm's pilot wave theory is de Broglie's objective wave-corpuscle dualism. On the ground of this idea, proposed by de Broglie in 1926 at Solvay Conference, each fundamental particle of physics is assumed to be constituted by a corpuscle and by a wave which surrounds it and accompanies it during its motion. As regards the non-relativistic problem, de Broglie suggested that the wave function of such an object was associated with a set of identical particles which have different positions and are distributed in space according to the usual quantum formula, given by $|\psi(x)|^2$. But he recognized a dual role for the wave function: on one side, it determines the probable position of the particle (just like in the standard interpretation), on the other side, it influences the position by exerting a force on the orbit. According to de Broglie, the wave function would act like a sort of pilot wave which guides the particles in regions where such wave function is more intense (De Broglie 1928).

Bohm's version of quantum mechanics is practically the de Broglie pilot-wave theory carried to its logical conclusion. The basic idea of Bohm's theory is in fact the idea that each elementary particle of physics is constituted contemporarily by a wave and a corpuscle and that here the wave has the role to guide the corpuscle during its movement. The wave is described mathematically by Schrödinger's wave function ψ.

In its classic works of 1952 and 1953, Bohm managed to develop a consistent mathematical model to de Broglie's objective wave-particle dualism (Bohm 1952 and 1953). Bohm showed that the movement of the corpuscle under the guide of the wave happens in agreement with a law of motion which assumes the following form $\frac{\partial S}{\partial t}+\frac{|\nabla S|^2}{2m}-\frac{\hbar^2}{2m}\frac{\nabla^2 R}{R}+V=0$ (where R is the amplitude and S the phase of the wave function, $\hbar$ is Planck's reduced constant, m is the mass of the particle and V is the classic potential). This equation is equal to the classical equation of Hamilton-Jacobi except for the appearance of the additional term $Q=-\frac{\hbar^2}{2m}\frac{\nabla^2 R}{R}$ having the dimension of an energy and containing Planck's constant and therefore appropriately defined quantum potential. The equation of motion of the particle can be expressed also in the form $m\frac{d^2\vec{x}}{dt^2}=-\nabla(V+Q)$, thus equal to Newton's second law of classical mechanics, always with the additional term Q of quantum potential. The movement of an elementary particle, according to Bohm's pilot wave theory, is thus tied to a total force which is given by the sum of two terms: a classical force (derived from a classic potential) and a quantum force (derived just from quantum potential) (Holland 1993).

Quantum potential must not be considered a term which is introduced ad hoc, contrary to the opinion of the supporters of the Copenhagen interpretation. Quantum potential plays an essential role in quantum formalism: in the plant of Bohm's theory, it emerges directly from Schrödinger's equation and without it energy should not be conserved. In fact, equation $\frac{\partial S}{\partial t}+\frac{|\nabla S|^2}{2m}-\frac{\hbar^2}{2m}\frac{\nabla^2 R}{R}+V=0$, taking into account that the quantity $-\frac{\partial S}{\partial t}$ is the total energy of the particle and that $\frac{|\nabla S|^2}{2m}$ is its kinetic energy, can be also written in the equivalent form $\frac{|\nabla S|^2}{2m}-\frac{\hbar^2}{2m}\frac{\nabla^2 R}{R}+V=-\frac{\partial S}{\partial t}$, which can be seen as a real energy conservation law in quantum mechanics: here one can easily see that without the quantum potential $Q=-\frac{\hbar^2}{2m}\frac{\nabla^2 R}{R}$ energy could not be conserved. It must be observed, as it was showed recently by Hiley, that quantum potential can be derived also by Heisenberg's formalism by choosing a particular representation for operators and also here such term must be present to assure the conservation of the total energy of the system (Hiley 2002).

Bohmian mechanics provides a possible description of the quantum reality which lies beyond the calculation rules of quantum conventional formalism. This theory has an ontology of particles. Each individual physical system is contemporarily described by its wave function (which evolves according to Schrödinger equation) and by the specification of the effective positions of the particles, whose evolution is governed by a guide equation which establishes that the speeds of the particles are determined by the wave function.

Therefore, in bohmian mechanics, the motion of the particles is somewhat "choreographed" by the wave function. Bohmian mechanics solves all the paradoxes of quantum mechanics, by eliminating strangeness and mysteries. In bohmian mechanics the indexes of measurement apparatuses always have a well defined orientation and thus a measurement problem does not exist. The interpretation of quantum individual processes in terms of well defined trajectories of particles excludes the possibility to introduce the collapse of the wave function. The wave function contains all the possibilities but not all the possibilities come true because the particles follow well defined and univocal trajectories which choose the possibility that must come true, and those that instead remain only potential.

Moreover, by introducing quantum potential, Bohm's theory makes manifest the most dramatic effect of quantum mechanics, the nonlocality. Bohm's theory shows clearly that nonlocal correlations between subatomic particles – and which constitute a fundamental feature of many-body systems – are caused by the action of quantum potential. For a many-body system, quantum potential acting on each particle is a function of the positions of all the other particles and thus in general does not decrease with distance. As a consequence, the contribution to the total force acting on the *i*-th particle coming from the quantum potential, i.e. $\nabla_i Q$, does not necessarily fall off with distance and indeed the forces between two particles of a many-body system may become stronger, even if $|\psi|$ may decrease in this limit. The equation of motion of the *i*-th in particle, in the limit of big separations assumes the form $m_i \frac{\partial^2 \vec{x}_i}{\partial t^2} = -[\nabla_i Q(\vec{x}_1, \vec{x}_2, ..., \vec{x}_n) + \nabla_i V_i(\vec{x}_i)]$ and thus depends on the coordinates of all the n particles of the system: this determines just nonlocal correlations in a many-body system. In virtue of the features of quantum potential, Bohm's theory turns out to be intrinsically olistic, in which "the whole is more than the sum of the parts". It is a merit of the pilot wave theory to show in such a direct way this property that, according to Bohm, "… is the newest and most fundamental ontological characteristic implied by quantum theory" (Bohm 1988).

Since 1979, Bohm's approach (thanks to the contributions, above all, of Philippidis, Dewdney, Hiley, Vigier) has allowed to explain, in visualizable terms, many experimental results (for example, classic double-slit experiment, tunnelling, trajectories of two particles in a potential of harmonic oscillator, EPR-type experiments, experiments of neutron-interferometry) (Philippidis et al, 1979; Dewdney 1987). In 1984, Bohm proposed then the idea to interpret quantum potential as a sort of "information potential": the particles in their movement are guided by the quantum potential just as a ship at automatic pilot can be handled by radar waves of much less energy than that of the ship. On the basis of this interpretation, the results of double-slit experiment are explained by saying that the quantum potential contains an active information, for example about the slits, and that this information manifests itself in the particles' motions.

Moreover, different proposals to extend bohmian mechanics to quantum field theory have been suggested. In particular, in this regard, a recent proposal of Dürr, Goldstein, Tumulka and Zanghì (2004) implies a dynamic according to which the particles can be created and destroyed and therefore implies that the deterministic evolution is interrupted at certain instants by a stochastic evolution. This dynamic takes place in a configuration space with a variable number of particles and is mathematically described by a markovian-type stochastic process. According to this dynamic, the particles' trajectories are parts of bohmian trajectories, with different numbers of particles, "sticked" among them by stochastic laws. Like in the conventional bohmian mechanics, the motion of the configuration is guided, although now in a stochastic way, by the wave function (which is now an element of Fock space). This version of bohmian field theory turns out to be in agreement with the probabilistic predictions of standard quantum field theory (Ghirardi et al, 1986). Moreover, it is interesting to observe that, although the theory is based on an ontology of particles, quantum field operators assume an important role in its construction: to provide a well defined relationship between space-temporal events and the "abstract" wave functions of quantum field theory.

3. GRW theory and the spontaneous localization

GRW theory, proposed by Ghirardi, Rimini and Weber since 1986, can be considered as one of the most significant and interesting models which treat the measurement problem with the reduction of the wave function. It renders in exact and not ambiguous manner (namely independently from the intervention of an external observer) when and how the wave function collapse has the superiority on Schrödinger equation. This theory starts from the hypothesis that all the elementary particles of physical world occasionally (in virtue of a fundamental physical law) stop to evolve in agreement with Schrödinger equation and undergo a spontaneous localization.

The main characteristics of the spontaneous localizations predicted by GRW theory are the following. Firstly, the effect of the localization is to make the wave function null outside the interval where the particle is localized and to make it unaltered in the same interval. More precisely, if the localization happens in a point q of space the wave function ψ is instantaneously changed into $\psi_q = \frac{\varphi_q}{|\varphi_q|}$ where $\varphi_q = \sqrt[4]{\frac{\alpha}{\pi}} e^{-\frac{\alpha}{2}(x-q)^2}\psi$. Here the quantity $\frac{1}{\sqrt{\alpha}}$ has the dimension of a length and represents the accuracy of the localization. Secondly, the probability for each particle to undergo a process of spontaneous localization turns out to be constant in time and is characterized by an average frequency λ. Finally, the model establishes that the spontaneous collapses take place favourably in the points where quantum mechanics affirm to be the most probability to find the particle in a measure of position (namely where the probability density is bigger in agreement with Born's definition).

In this way, GRW theory introduces two parameters, the average frequency λ of the localization and the spatial accuracy $\frac{1}{\sqrt{\alpha}}$ of the localization which must be assumed as two new nature constants. The particular choice $\lambda = 10^{-16} Hz$ and $\frac{1}{\sqrt{\alpha}} = 10^{-7} m$ assures that a free particle localizes spontaneously only in an average time $10^{-8} - 10^{-9}$ years (namely that isolated microscopic systems hardly ever collapse) while for a macroscopic body (such as in a measurement) the spontaneous localization happens in about 10^{-7} seconds.

Contrary to what happen in the orthodox interpretation, inside GRW theory the wave function collapse is not seen as a consequence of the intervention of the observer. On the basis of the proposal of Ghirardi, Rimini and Weber, no observer performs no measure: it is the same nature that chooses to make this processes happen, according to casual rules but with precise probabilities. GRW theory allows the solving of the measurement problem without ascribing a special role to the observer: the only observer that is necessary to determine the wave function collapse is an unanimated apparatus which amplifies the microscopic events.

The most important characteristic of GRW theory is that if at a certain time the wave function of a macroscopic system is a superpositions of two wave functions, which have support in distinct macroscopic configurations, then, in less than 10^{-7} seconds and with probability near to 1, at least a spontaneous event of localization realizes which determines the collapse into one of the two terms of the superposition. In other words, without the intervention of an external observer, but only in virtue of the dynamic structure of GRW theory, the macroscopic superposition spontaneously transforms into one of the wave functions which compose it. And this happens in agreement with the probabilities of standard quantum mechanics.

The wave function of GRW theory would thus provide a complete and satisfactory description of physical systems. But is thus really? The answer is no for the following reason: although GRW theory speaks about configurations, the configuration of a system does not represent, in this theory, the set of the positions of the particles constituting the system, contrary to what happens in bohmian mechanics or in classical mechanics. The particular language is improper for this theory. In GRW theory no principle exists according to which the configuration of a system represents the set of the positions of the particles in physical space: in this theory there are not positions in space because there are not particles! While in bohmian mechanics and in classical mechanics the notion of material points which move in 3-dimensional Euclidean space is a primitive notion (bohmian mechanics and classical mechanics are theories of particles), on the contrary what is primitive in GRW theory is the wave function. How is it possible to go out from this impasse?

Ghirardi proposed that the primitive notion in GRW theory is not the wave function, but a scalar field in space-time univocally determined by the wave function (Ghirardi 2007). On macroscopic scale this field can be identified with the mass density of physical objects and the description that hence emerges results in agreement with our daily experience as regards the way according to which the mass of the objects is distributed in physical space. The image of the physical world which derives from this scheme (that we can also call GRWm theory where *m* stays for mass), although is different from bohmian mechanics and from that suggested by conventional formulations of quantum mechanics, does not imply contradictions with the predictions of standard quantum theory. This ontology remembers the Schrödinger original interpretation of the wave function in terms of continuous density of electric charge. GRWm theory is a theory based on an ontology of field in the same way bohmian mechanics is a theory characterized by an ontology of particles in motion in physical space (Allori et al, 2006). In this theory, the role of the wave function (which evolves according to the non-linear and stochastic equations of the original GRW theory) is to determine the temporal evolution of the variable describing the primitive ontology of the theory, namely the scalar field.

However, both original GRW theory and GRWm theory cannot explain in a causal way what happens in an apparatus during a measurement process. In GRW and GRWm theories, the laws responsible of the spontaneous localizations do not allow us to predict what particle of the index will undergo the collapse and in what state among those in which it potentially can arrive. As regards what happens in the index of the measurement apparatus, in the dynamic reduction theories the probabilism plays an important role. In synthesis, GRW and GRWM theories, contrary to bohmian mechanics, cannot provide a causal ontology of the measurement processes.

4. Conclusions

We conclude with some considerations concerning the common structure and the differences between bohmian mechanics and GRWm theory in reference to the ontology of the events. Firstly, by analyzing carefully these theories, a very important philosophical lesson emerges: in the structure of these theories we can seek some very general characteristics which are in fact common to all the "quantum theories without the observer". These characteristics can be so synthesized:

- the theory is based on a clear ontology, the primitive ontology, which describes the matter in space and time: the particles in bohmian mechanics (both in its original version and in its extension to quantum field theory), the mass density in GRWm theory
- there is a wave function which evolves according to Schrödinger equation in an exact manner or, at least for microscopic systems, in an approximate manner only (in case with stochastic and non-linear corrections)
- the wave function rules (in case in a stochastic way) the temporal evolution of the variables which describe the primitive ontology
- the predictions are in agreement with those of standard quantum theory.

However, bohmian mechanics and GRWm theory present also some important differences regarding the ontology of the events, the quantum image of the reality that they predict. In fact, in bohmian mechanics the background ontology is certainly realistic and causal (in virtue of the presence of quantum potential). This formulation was elaborated just with the aim to re-establish classical realism in quantum mechanics, by interpreting the quantum formalism in realistic and objective way and by negating the central role of the observer and of the measurement action. Instead GRWm theory predicts a different type of events and thus a different background ontology: here the wave function collapse is described from the dynamic characteristics of the theory and nothing is said about the physical microscopic reality pre-existing to the measurement or to an (improbable) spontaneous localization event.

However, we can say that both bohmian mechanics and GRWm theory offer themselves as good candidates for the precise definition of a consistent quantum reality just because both avoid to ascribe a special role to the observer. They constitute a starting point in order to build up a coherent view of the quantum reality. This opinion is in part supported by J.S. Bell who, in his last work, wrote that the two only alternatives to standard interpretation were according to him represented by GRW theory and Bohm's formulation of quantum mechanics.

REFERENCES

Allori V., Goldstein S., Tumulka R., Zanghì N. (2006). On the common structure of bohmian mechanics and Ghirardi-Rimini-Weber theory, quant-ph/0603027.

Bohm D. (1952). A suggested interpretation of quantum theory in terms of hidden variables, Phys. Rev., 85, 166-193.

Bohm D. (1953). Phys. Rev., 89, 1953.

Bohm D. (1988). An ontological foundation for the quantum theory, in (a cura di) P. Lahti e P. Mittelstaedt, Symposium on the foundation od modern physics – 1987, World Scientific Publishing Co.

Bohr N. (1961). Teoria dell'atomo e conoscenza umana, Boringhieri, Torino.

De Broglie L. (1928), in "Solvay Congress (1927), Electrons and photons: rapports et discussions du Cinquime Conseil de Physique tenu Bruxelles du 24 au Octobre 1927 sous les auspices de l'Istitut International de Physique Solvay", Paris, Gauthier-Villars.

Dewdney C. (1987). Calculations in the causal interpretation of quantum mechanics, in Quantum Uncertainties – Recent and Future Experiments and Interpretations, Plenum Press, New York, 19-40.

Dürr D., Goldstein S., Tumulka R., Zanghì N. (2004). Bohmian mechanics and quantum field theory, Phys. Rev. Letters, 93, 090402.

Dürr D., Goldstein S., Tumulka R., Zanghì N. (2005). Quantum hamiltonians and stochastic jumps, Communications in Mathematical Physics, 254, 129.

Fiscaletti D. (2003). I fondamenti nella meccanica quantistica. Un'analisi critica dell'interpretazione ortodossa, della teoria di Bohm e della teoria GRW, CLEUP, Padova.

Fiscaletti D. (2007). I gatti di Schrödinger. Meccanica quantistica e visione del mondo, Muzzio Editore, Roma.

Hiley B.J. (2002). From the Heisenberg Picture to Bohm: a New Perspective on Active Information and its relation to Shannon Information, in Proc. Conf. Theory: reconsiderations of foundations, Växjö University Press, Växjö, Sweden, 141-162.

Holland P.R. (1993). The quantum theory of motion, Cambridge University Press, Cambridge, Massachussets.

Philippidis C., Dewdney C. and Hiley B. (1979). Il Nuovo Cimento, 52B, 15.

Ghirardi G.C., Rimini A., Weber T. (1986). Unified dynamics for microscopic and macroscopic systems, Phys. Rev., D34, 470-491.

Ghirardi G.C. (2007). Some reflections inspired by my research activity in quantum mechanics, J. Phys. A.: Math. Theor., 40, 2891-2917.