The Holistic Aspect of the Phenomenon of Entanglement

ROBERTO ANGELONI

§1. Introduction

THE THESIS OF HOLISM has found interesting applications in connection with various interpretations of quantum theory. As is known, the general definition of holism states: the whole is more than the sum of its parts. This claim is relevant in the sense that it entails one of the main differences between classical physics and quantum physics (Healey 2009). That is to say: while, in classical physics, a system can be analysed into parts, whose state and properties determine the whole they compose, such a line of reasoning cannot be applied to quantum mechanics. To say it with the words of Healey, even when a compound system has a pure state, some of its subsystems may not have their own pure states (Healey 2009). Following this consideration on the quantum theory, Schrödinger called such composite subsystems as "entangled".

Quantum entanglement is a quantum-mechanical phenomenon, which describes the quantum states, for instance, of two objects, in such a way that measuring the quantum states of one of the objects under considerations conditions the measurement of the other objects, even though the two objects may be spatially separated. Furthermore, a characterization of quantum entanglement can be given in terms of non-separability, according to which two or more systems are non-separable if and only if it is only the joint state of the whole that completely determines the state-dependent properties of each system and the correlations among these systems (Esfeld 2004).

I will use recent literature to distinguish methodological holism from metaphysical holism. Methodological holism states that the best way to understand the behaviour of a complex system is to treat it as a whole, whereas metaphysical holism maintains the idea that the nature of "some wholes" is not determined by the nature of their component parts (Healey 1991, 2009).

R. Angeloni (✉)
Independent Researcher, Italy
e-mail: robert_angeloni@hotmail.com

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Metaphysical holism can be divided into three categories: ontological holism, physical property holism, and nomological holism.

By definition, ontological holism states: there are physical objects that are not wholly composed of basic physical parts. Physical property holism deals with the issue that the physical properties of some objects are not determined by the physical properties of their parts. According to nomological holism, some objects obey laws that are not determined by fundamental physical laws governing the structure and behaviour of their basic physical parts (cf. Healey 2009).

The concept of holism will be analysed and compared in relation to the views expressed by Bohr and Schrödinger in order to assess the characteristic traits of their respective holistic approaches starting from their early works. Furthermore, I will show the extent to which the concepts of holism and non-separability played a role in determining Bohr's and Schrödinger's viewpoints with respect to the entanglement.

In 1935, Einstein, Podolsky, and Rosen wrote a paper in which a thought-experiment was presented, which brought to light some paradoxical consequences stemming from the accepted formulation of quantum mechanics. This paradox confirmed the existence of quantum entanglement as a consequence of the Copenhagen interpretation of quantum mechanics, and Schrödinger's view, which were incompatible with the postulate of the limit of the velocity of light according to Einstein's theory of special relativity.

§1.2 Holism and non-separability in Niels Bohr's philosophy of physics

According to literature on Niels Bohr (1885-1962), elements of holism seem traceable back at least to the definition of the stationary states (1912-1913), and perhaps to his early work on the electron theory of metals published in 1911.

Norton Wise, for instance, has argued that Bohr believed the discontinuity of Planck's oscillators and the associated expression of entropy derived from non-mechanical, *holistic* phenomena among collections of electrons (Norton Wise 1997, p. 415).

Following this interpretation, Bohr's advance in 1913 may be also regarded as a decision to ascribe holistic features to single atomic systems rather than to the electron gas. This breakthrough happened in the context of Bohr's work on Rutherford's nuclear planetary model of the atom and in connection with discontinuous radioactive transitions. Bohr believed that for an atom in a stationary state, the electrons, the nucleus and their Coulomb field had to be regarded as an integral unit. Similarly in 1911-1912, he had supposed that Planck's discrete oscillator states derived from collective motion in an electron gas (Norton Wise 1997).

However, we should be cautious about ascribing an explicit holistic outlook to Bohr immediately from the formulation of his first atomic theory. In 1913 Bohr *implicitly* treated transitions between stationary states as individual processes, implying the individuality of the quantum of action (Planck's *h*) as a starting point. However, it was only in the late 1920s that Bohr started to speak about the individuality of quantum processes. It was not until his later essays that the expressions "individuality", "indivisibility", "wholeness", and "atomicity" appeared in connection with the quantum of action.

What precisely did Bohr think about the holistic aspects of atomic processes?

Bohr scholarship seems to have overlooked the problem of the conceptual shift in the role of the quantum hypothesis from 1913 to the subsequent formulation of the theory. Indeed, a conceptual shift seems to characterize the role and function of the quantum of action from 1913 to 1927 within Bohr's scientific theories.

In 1912-1913 Bohr had already become aware of the discontinuity inherent in atomic processes. From then on, Bohr strove to demonstrate *the existence of stationary states*[1]

In the 1927 Como Lecture, "The Quantum Postulate and the Recent Development of Atomic Theory", Bohr used the expression "discontinuity, or rather individuality" to refer to the "quantum postulate".

> Notwithstanding the difficulties which, hence, are involved in the formulation of the quantum theory, it seems, as we shall see, that its *essence* may be expressed in the so-called quantum postulate, which attributes to any atomic process an *essential* discontinuity, or rather individuality, completely foreign to the classical theories and symbolized by Planck's quantum of action (Bohr 1929, p. 53. Italics by the present author).

In my view, there is a conceptual leap from the "discontinuity" of 1913's quantum postulates and the "essential discontinuity, or rather individuality, completely

1 Bohr used this expression in a lecture given to the Chemical Society in Copenhagen (2 December 1919), 'On the program of the newer atomic physics': "It will be seen that these experiments (Franck-Hertz experiments from 1913) give the most direct experimental evidence imaginable for the existence of stationary states of atoms, assumed originally on purely theoretical grounds to account for the peculiar formulas holding for the frequencies of the spectra of the elements" (*NBCW* 3, 222).

foreign to classical physics" of 1927 Como Lecture. In addition, we cannot forget that as a consequence of the publication of Heisenberg's 1925 reinterpretation paper, the second postulate, the frequency rule, was dropped from the new matrix theory, although Schrödinger's version of quantum mechanics allowed its provisional revival.

In 1927 Bohr thought he had already succeeded in defining stationary states. He claimed, indeed, they expressed the very essence of the quantum theory.

What we can take for granted is the fact that in 1913 Bohr had only *assumed* the existence of the stationary states, while in 1927 they had become an *essential* part of the new quantum theory.

Furthermore, we should consider that in 1925 the *existence* of stationary states was regarded as being as natural a feature of the theory as the existence of discrete vibration frequencies in classical theory (Heisenberg-Born-Jordan 1925, p. 558). Specifically, the Copenhagen-Göttingen School regarded the stationary states as mathematically deducible in the framework of the new matrix mechanics. The difference between the stationary states of Heisenberg's reinterpretation paper (and the three-man paper as well) and the "stationary states" presented in Bohr's Como lecture rests upon the fact that in 1925 Heisenberg had managed to obtain only a mathematical value that expressed the stationary states. It was in the light of Schrödinger's wave mechanics, and of the Davisson-Germer experiments on the reflections of electrons in crystals that Bohr, on his side, was able to define the "stationary states" as an essential part of the new quantum theory, as Bohr himself admitted some years later. In the unpublished manuscript "Philosophical foundations of the quantum theory", written before the 1927 Como lecture, Bohr claimed that the stationary states were no longer a separate assumption, and had become a proper element of subatomic phenomena.

Bohr's quotation hence represents a further development of Heisenberg's considerations on the stationary states given in his reinterpretation paper:

> The quantum theory has entered a new stage in which the existence of stationary states does not appear as a separate postulate, but where each such state appears as *a possible proper vibration of the wave equation*, similar to the harmonic waves in free space representing a component of a radiation field (*NBCW* 6, p. 70, Italics by the present author).

Why was this "individuality" and the later additions of "indivisibility" and "wholeness" so recurrent in Bohr's writings, and why did it seem so important in Bohr's thinking?

Bohr thought of the quantum of action and the stationary states (Bohr used these two terms as synonyms from 1927) as an element of irrationality bringing about a discontinuity in quantum phenomena that must be rationally defined, as is clearly stated in his "On the Quantum Theory of Line-Spectra" from 1918.

In this regard, since its introduction (and in connection with the concept of energy quantization) the quantum of action was seen as an "external" and irrational element, and a theory had to be developed to re-establish the continuity and rationality of physical science. Furthermore, this is an issue that links with an important aspect of Bohr's philosophical interpretation of quantum mechanics: the meaning of a word demands continuity. This consideration also leads us to grasp the importance of the indispensability of classical concepts in Bohr's philosophy of physics.

Bohr was firmly convinced that the causal spatio-temporal description of classical physics presupposes continuity, as this description is intrinsically connected with the organization of our sensory experience. The concepts of classical physics are based on our sensory experience, although these concepts break down when they describe quantum phenomena.

From 1928 Bohr constantly spoke of the failure of the forms of perception adapted to our ordinary sensory impressions. Bohr included causality as well as space and time in the forms of perception: "Causality may be considered as a mode of perception by which we reduce our sense impressions to order" (Bohr 1929, pp. 116-117).

Bohr's inappropriate use of "forms of perception" with respect to causality probably derives from Harald Høffding's misleading interpretation of Kant's *Transcendental Aesthetic.*

As is well known, according to Kant, causality is a category, a concept of understanding, rather than a form. Høffding, a professor of philosophy at Copenhagen, a friend of Bohr's father and Niels' mentor, linked continuity, causality, space and time as forms of perception, contrary to Kant's usage (Høffding 1908, pp. 52, 58, *see* Murdoch 1987).

Moreover, Høffding regarded continuity as an essential condition that the forms of perception and the categories of cognition are required to possess. The forms of perception are thus the means by which we organize our perceptual experience. They express the conceptual structure of classical physics, through which the macroscopic world can be interpreted.

However, the classical forms of perception are not necessarily applicable to the microphysical world. Coherently, in 1926 Bohr wrote to Schrödinger: "the definition of every word essentially presupposes the continuity of phenomena and becomes ambiguous as soon as this presupposition no longer applies" (Letter from Bohr to Schrödinger, 2 December 1926, *NBCW* 6, p. 462).

In this view, ordinary language is designed in order to organize our sensory experience and it presupposes the condition of continuity. If this presupposition failed, ordinary language, including the models in terms of which we interpret physical theory, would become ambiguous.

The discontinuity and individuality of the quantum of action brought about a problem of visualizability, which is the characteristic trait of classical theory, but is denied to quantum physics.

The individuality of the quantum of action pertains to a general conception of quantum reality, raising doubts on the validity of the ontological interpretation of quantum mechanics "in terms of an objective stochastic process" (Bohm 1993).

Bohr and Heisenberg argued that in the measurement of p and x (representing position and momentum variables of a particle), the maximum possible accuracy given by the uncertainty principle p x > h is a limitation on the possible accuracy and relevance of our knowledge of the observed system.

If we take Bohr's amendment to Heisenberg's microscope argument into account, we shall arrive at the conclusion that the ambiguity in attributing the location of a point P is bound to the wave nature of the quantum that links the point P to the focal point Q of the microscope lens.

As David Bohm explained: "The Quantum has a momentum $h\nu/c$ and it produces a change of momentum in the particle p = $h\nu \sin \theta/c$ where θ is the angle through which the quantum has been scattered by the particle. The individuality of the quantum guarantees that its momentum cannot be reduced below this value" (Bohm 1993, p. 15).

This position undermines the ontological interpretation of quantum mechanics, because the basic properties of the particle (position and momentum) are not simply uncertain to us, rather there is no other way to give a more accurate definition beyond the limits set by the Heisenberg microscope argument. This argument brought about a new way of describing the experiment, in which the phenomenon is seen as an entire whole that cannot be analysed into parts.

Bohr was convinced of the impossibility of finding a clear demarcation between the observing apparatus and the observed object because of the indivisibility and individuality of the quantum of action. It follows from Bohr's argument that very little can be said about quantum ontology, that is, on the existence of particles and fields considered as being essentially independent from the observer. Bohr never spoke of a quantum object standing on its own, he regarded the phenomenon (the interaction between observing apparatus and observed object) as an un-analysable whole. Bohr's holistic position was a consequence of his assumptions on the nature of the quantum of action, which is indivisible and produces unpredictable and uncontrollable consequences in each individual case (Bohm 1993, p. 14). On such a basis, even Bohr's interpretation of the phenomenon of entanglement is a mere consequence of his assumptions with regard to the quantum of action.

This is a point that Bohr clearly stressed in his 1935 reply to the EPR (Einstein-Podolski-Rosen) paper:

> The impossibility of a closer analysis of the reactions between the particle and the measurement instrument is indeed no peculiarity of the experimental procedure described, but is rather an essential property of any arrangement suited to the study of the phenomena of the type concerned, where we have to do with a feature of individuality completely foreign to classical physics (Bohr 1935, p. 697).

§3. Holism and non-separability in relation to Schrödinger's interpretation of quantum mechanics

Schrödinger's interpretation of quantum mechanics is characterized by a holistic conception of nature, which can be recognized as early as his works on statistical thermodynamics in the mid-twenties.

Schrödinger's work in statistical physics (1912-1925) can be divided in three main periods (Darrigol 1992, p. 255): the first in which he favoured the molecular view point; the second in which he switched to a holistic statistical method, while still analysing the global state of the system in terms of individual molecules; the third in which he shifted to an entirely holistic approach.

Elements of holism in Schrödinger's theoretical attitude trace back to his adhesion to the Bohr-Kramers-Slater theory (BKS) (known as the theory of virtual oscillators) with the paper "Bohrs neue Strahlungshypothese und der Energiesatz" (Bohr's new radiation theory and the energy principle) from 1924.

Can we speak of an organic and consistent holistic project put forward by Schrödinger until the end of his career?

The legitimacy of the question lies in the fact that the fundamental concepts of such a holistic approach had to coexist with some concepts of the particle-like interpretation of quantum physics from the outset of Schrödinger's scientific work.

As mentioned above, Schrödinger's paper on the so-called theory of virtual oscillators offers the first glimpse of his holistic attitude. The BKS paper aimed to reconcile the quantum properties of atoms with the continuity of the electromagnetic fields. The BKS theory hypothesized that atoms communicate with one another through a spatio-temporal mechanism, which is "virtually equivalent with the field of radiation" of classical electromagnetism. But it is not the virtual field that bears energy, it rather induces transitions between the stationary states of atoms.

Schrödinger welcomed almost every element of the theory. He wrote to Bohr:

> The renunciation of causality touches me extraordinarily sympathetically. As pupil of the venerable Franz Exner I have been on intimate terms for a long time with the idea that probably no microscopic lawfulness but perhaps 'absolute accident' forms the foundation of our statistics, and that perhaps even the energy and momentum principles are only statistically valid (Schrödinger to Bohr, 24 May 1924, in Darrigol 1992, p. 267).

In the paper at issue, Schrödinger pointed out that the average squared fluctuation of the energy of a gas of Bohr atoms interacting in the BKS manner via the virtual fields would increase linearly in time.

The linear increase of fluctuations, as Schrödinger wrote, could be distributed over an ever-increasing number of atoms. Bohr regarded such a remark as a serious objection to the BKS theory, although it was not Schrödinger's intention to refute it. In fact, Schrödinger himself was searching for minor changes to be applied to the theory. For instance: by increasing the size of the system, the deviation would be reduced; in addition, regarding such system as a subsystem of a more extended system would compensate the infinite increase of temperature. Here Schrödinger's recourse to descriptive holism in supporting his idea is evident:

> A certain stability of world events *sub specie aeternitatis* can only exist through the connection of each individual system with the rest of the world. A separated individual system would be, from the point of view of the all, chaos. The connection is needed as a continuing regulation, in relation to energy, the system would wander about aimlessly. – Is it gratuitous play with thoughts to let one perceive a similarity with social, ethical, and cultural phenomena? (Schrödinger 1924, from Darrigol 1992, p. 268).

The system does not wander about at random if the connection of the given system with the rest of the world is ensured. The kind of holism to which Schrödinger alludes to here is required in order to describe atomic reality and to account for the stability and therefore the existence of the world. For this reason, it can also be defined as descriptive, as it *represents* the state of things as regards the subatomic phenomena.

Descriptive holism is also used in the social sciences to define a group of social entities (villages, for instance) that have been put in a wider context. It is worth noting that Schrödinger concluded the paragraph quoted above by placing emphasis on the similarity between quantum phenomena and social phenomena.

As I see it, there is a conceptual transition from the descriptive holism of his 1924 paper to the constitutive holism arising from the 1925 and 1926 works: "Bemerkungen über die statistische Entropiedefinition beim idealen Gas" (Remarks on the statistical definition of entropy for an ideal gas), 1925; "Zur Einsteinschen Gastheorie" (On Einstein's theory of gases), 1926; "Die Energiestufen des idealen einatomigen Gasmodels" (The energy states of the ideal monoatomic gas model), 1926.

Schrödinger became aware that holism was intrinsically (and *constitutively*) connected with the statistical behaviour of quantum systems, as emerges from the Communication addressed to the Berlin Academy in 1925. On this occasion, Schrödinger began to develop his ever more stringent version of holism, in which he showed that Born's and Brody's quantum theoretical derivation of the specific heat of solids at high temperature could be replaced by a simpler classical derivation based on Gibbs' canonical method. As Darrigol has clearly shown, this is the first occurrence of the *holistic method* (*see* methodological holism) in Schrödinger's writings. Until then Boltzmann's distribution for *individual* molecules had been Schrödinger's main reference point, while in 1925's Communication at the Berlin Academy he went to rely on the concept of *ensembles* through the application of Gibbs' method (Darrigol 1992, p. 247).

It is worth noticing a *tension* between the theoretical feature of the definition of entropy, which expresses a holistic character, and the "practical" necessity of breaking the picture into individual molecules, which is entailed in carrying out calculations.

There is a line of demarcation between Schrödinger's holistic view and the aspects of holism arising from Bohr's approach. Indeed, in spite of his holistic standpoint, Schrödinger raised doubts on the fundamental role of stationary states and quantum jumps (postulate of the frequency rule) in the new quantum theory. As is evident, there is irony here. *Wholeness* and indivisibility were also implicit aspects of the two quantum postulates of Bohr's 1913 model of the hydrogen atom. Schrödinger argued that, in his view, the "orthodox" interpretation of quantum mechanics was fuelled by the particle-like ontology. For this reason Schrödinger aimed to eradicate quantum jumps and corpuscolarism, as he regarded these fundamental assumptions as a remnant of classical ontology.

With regard to quantum jumps, Schrödinger claimed: "it seems to me that there is a very strange relation between Heisenberg's uncertainty relation and the claim of discrete quantum states. On account of the former, the latter can really not be experimentally tested" (letter from Schrödinger to Bohr, 5 May, 1928, from *NBCW* 6, p. 47). This is a crucial point in Schrödinger's critique of the Copenhagen interpretation of quantum mechanics.

Schrödinger's line of thought was characterized by the rejection of any descriptive discontinuity, which also forms the basis of his "treatment of the measurement problem" (Bitbol 1996, p. 110).

The measurement problem and Heisenberg's uncertainty relations are closely related. As we have seen, Heisenberg and Bohr regarded the uncertainty relations as the expression of an undeterminable disturbing influence exerted on an object by the very act of measurement.

How can we describe Schrödinger's position with regard to the measurement problem?

In the 1935 "cat" paper, Schrödinger introduced the word entanglement and regarded the concept of the "wave-function" as a "catalogue of information".

According to this interpretation, if two interacting systems "enter a situation in which they influence each other, and separate again, then there occurs regularly that which I have just called entanglement of our knowledge of the two bodies" (Schrödinger 1935a, p. 161).

What did the measuring process yield? Schrödinger's answer does not leave any doubt: if we apply the measuring process to a combined system (measuring apparatus and measured object) we are able "to avoid (…) the singular quantum jump of the ψ-function" (Schrödinger 1935a, p. 161).

The ψ-function of the measured object has become entangled with the ψ-function of the apparatus. As a consequence, one can deduce that the measuring process leads to a holistic catalogue of information for the combined system that excludes the quantum jumps.

Secondly, Schrödinger used Heisenberg's uncertainty relations in order to undermine the concept of particle. According to Heisenberg, "(…) the uncertainty relation specifies the limits within which the particle picture can be applied" (Heisenberg 1930, p. 15).

Schrödinger sought to demonstrate, instead, that the particle picture is always unsuitable. His emphasis on the violations of Heisenberg's uncertainty relations when they are referred to past events can also be seen as part of Schrödinger's strategy against the particle-like approach.

Let us focus for the purpose on the uncertainty relations. One cannot know the position and the momentum of a given particle because any measurement of one variable (position, for instance) alters the value of the other variable (momentum, for instance). Heisenberg then derived that the uncertainty relations cannot refer to the past, as he was convinced that the "knowledge of the past is of a purely speculative character, since it can never (…) be subjected to experimental *verification*" (Heisenberg 1930, p. 15). On the other side, in Schrödinger's view, the problem of the retrospective ascription of values arises from the fact that Heisenberg focused on a well-defined object, that is a particle; a conclusion that could be avoided by adopting a time-independent Schrödinger equation in the non-relativistic limit in opposition to the particle-like approach.

The concept of particle was one of the main points of disagreement between Schrödinger's and Bohr's conceptions with regard to holism and non-separability. This is one of the reasons for which Schrödinger was critical towards Bohr's complementarity, viz. wave- particle complementarity and conjugated variables complementarity. The progressive rejection of corpuscolarism would have brought Schrödinger to a new "ontology" that ascribes criteria of "reality" not to particles but to ψ-waves.

The first consequence of the rejection of corpuscolarism concerns the definition of the wave function. A wave-function is clearly defined when *only* one of the two conjugated variables (position or momentum) has been ascribed a precise value, whereas the corpuscular representation would lead one to ask for the precise value of the momentum of the particle at the very instant when the position observable has been measured. Schrödinger developed this argument when Bohr formulated the principle of complementarity.

Secondly, Schrödinger very early – by 1926 – recognized in the wave functions the attitude to embody the law-like connection between experimental events that seemed to be an index of their "reality". This interpretation is grist for the mill of neo-Kantianism, as Schrödinger's concern are not localized events, rather laws and relations, which become necessary with respect to the specific domain which they refer to. In this regard, the entanglement of our knowledge of the two bodies would be nothing but the recognition of a general law-like connection between two interacting systems.

Finally, in his later writings – in the context of the Dublin seminars (1949-1950) – Schrödinger went on to define the wave functions' statistical distribution as they only have one "objective feature". He did this by introducing a classification regarding particles and ψ-waves. Particles are first-level entities, which cannot be objectivized. Ψ-waves are second -level entities, embodying statistical regularities, which can be objectivized. Particles can produce localized events, while second-level entities like ψ-waves embody statistical regularities. The objectivity of ψ-waves rests in their being more than a mathematical tool, showing the character of an invariant observation. In this sense they can offer a basis for a new "ontology", although the "ontology" presented here can be conceived as an objective reference system or as a structure, not in the traditional sense of grasping the things as they are "out there".

Schrödinger abandoned his early *ontological* interpretation of wave functions by rejecting the idea of a "one-to-one correspondence" between observable facts and ψ-waves, although in the 1950s he still regarded the ψ-function as a picture "of something" *in abstracto* (Bitbol 1996, p. 38), which precluded the "factuality" of the wave function, but not its "reality".

As mentioned above, between 1925 and 1928 Schrödinger became fully aware of the irreducibly holistic character of the wave-mechanical formalism in connection with the $3n$-dimensionality of the ψ-waves:

> The ψ-waves is in general (…) not a function of time and place, but it is a function of one, two, three … places if the classical model of the system is made of one, two, three mass points. This is a very remarkable and deep-lying circumstance, which – I should mention – already makes the conception of the ψ-function as a collection of local states difficult (Schrödinger 1929, from Darrigol 1992, p. 259).

The importance of Schrödinger's holistic standpoint in relation to the analysis of the entanglement became evident in 1935 in his reaction to the EPR paper:

> When two systems, of which we know the states by their respective representatives, enter into temporary interaction due to known forces between them, and when after a time of mutual influence the systems separate again, then they can no longer be described in the

> same way as before, viz. by endowing each of them with a representative of its own. I would not call that one but rather the characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought (Schrödinger 1935b, p. 555).

Following previous work on statistical mechanics, in which the holistic stance was already present, in 1926 Schrödinger gave an account of Einstein's theory of gases in terms of holistic structures of quantum mechanics (Bitbol 1996, p. 22). In 1927 he provided a precise mathematical form of this in the article "The exchange of energy according to wave mechanics", and later he went to formulate the concept of entanglement of wave functions in the articles "The current situation in quantum mechanics" and "Discussion of probability relations between separated systems" from 1935.

§4. Final remarks: a comparison between the two stances on holism and non-separability

I return briefly to the disagreement between Bohr and Schrödinger with regard to their holistic views. As has been mentioned, Bohr's holistic outlook became evident in the mid- 1920s, although elements of holism seem to have emerged implicitly as from 1912-1913 in connection with the formulation of the first model of the hydrogen atom. However, it is indisputable that in the 1927 Como Lecture Bohr termed the quantum of action as "indivisible", and on that he regarded the "indivisibility" of Planck's constant as the essence of the quantum theory. In fact, the individuality of the h guarantees that its momentum cannot be reduced below this value. This is a position that undermines the ontological interpretation of quantum mechanics: the existence of particles and fields as being essentially independent from the observer, as the basic properties of a particle (position and momentum) are not simply uncertain to us, rather there is not any other way of giving a more accurate definition beyond the limits set by the Heisenberg microscope argument.

As already noted, Bohr's holistic position was a consequence of his assumption that the quantum of action is indivisible and produces unpredictable and uncontrollable consequences in each individual case. What is the character of Bohr's holism?

I argue that Bohr's view seems to endorse a kind of ontological holism, the reason being that Bohr regarded the "phenomenon" (the interaction between measuring apparatus and quantum object) not as composed of independently physical parts, but as an apparatus-object whole. Moreover, if the quantum object may be taken to exist outside the context of the phenomenon, little can be said about its properties. This is a conclusion that fits neatly with the definition of ontological holism given at the beginning of this paper.

Bohr's holism was a natural consequence of his conception of the quantum of action. This conception allowed him to accept and assimilate the EPR correlations much more than Schrödinger did, as quantum entanglement was already logically presupposed in the 1927 Como lecture.

From 1935 onwards, Schrödinger continually expressed his concern and scepticism about the problem of non-locality of quantum mechanics that he recognized as the characteristic trait of the theory. Such a remark was a straightforward consequence of considerations concerning the quantum theory of measurement, as a measurement operation leads to entanglement between the measuring apparatus and the object being measured.

Schrödinger doubted if the phenomenon of entanglement was not just an effect due to an unjustified application of the "non-relativistic formalism" to conditions which do not fall in its range of validity. He suggested that the reason for the inadequacy of "ordinary quantum mechanics" might be that the entanglement appears to involve an "un-retarded *actio in distans*", which can only occur if the system is "small enough (…) to be able to neglect the time that light takes to travel across the system" (Schrödinger 1936, p. 451).

How can we explain Schrodinger's reluctance to accept the phenomenon of entanglement, one of the physical consequences of wave mechanics? In retrospect, if we turn our attention to Schrödinger's later positions, this reluctance seems to derive from a persistence of his corpuscularian representation in the holistic framework of wave mechanics (Bitbol 1996).

However, Schrödinger's doubts would have been swept away by focusing on the structure of ψ-functions, and relinquishing the localized isolated parts – in which the aspect of separability would prevail. This is what Schrödinger ultimately did by renouncing to deal with the issue of the possible disappearance of the entanglement features of the quantum mechanical description of phenomena in a future relativistic theory. He pointed out that this entanglement was just an appropriate expression of the fundamental lack of individuality of the so-called particles; that is to say: the priority given to the whole over the artificially isolated parts. This view can be summarized in the well-known quotation: "The best possible knowledge of a whole does not imply the best possible knowledge of its parts – and here is the mystery (Schrödinger 1935b, p. 555).

Among the criteria for ascribing "reality" to ψ -waves we have found the "effectiveness" of the wave functions, that is, their ability to embody the law-like connection between experimental events. As a matter of fact, when Schrödinger rhetorically asked himself: "…are we genuinely interested in the precise value of a variable like x or p?" He answered *no*: "We are interested in general laws, not in special facts" (Schrödinger 1995, p. 81). Schrödinger's attitude also has a strong neo-Kantian equivalent, as it considers laws, and relations, as necessary with respect to the specific domain to which they refer. In this view, the entanglement of our knowledge of the two bodies is but the recognition of a general law-like connection between two interacting systems.

Starting with his early works Schrödinger expressed a non-metaphysical approach to the philosophy of physics that became manifest in the attribution of some kind of "reality" to ψ-waves. Nevertheless, we should be cautious about the connotations of the words "ontology" and "reality". Ultimately, Schrödinger accepted only a restricted kind of ontology corresponding to the definition of an appropriate system of entities; that is, a structure of relations. Finally, Schrödinger's interpretation of fundamental themes of quantum mechanics, such as holism, separability, particle-like VS wave-like approach, and the EPR argument, seems controversial in many respects, and in some cases even quixotic.

In any case Schrödinger's originality lies in the fact that he discussed the aspect of holism in the light of his previous work in statistical physics, which made him become aware that holism was intrinsically related to the statistical behaviour of quantum systems.

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The Holistic Aspect of the Phenomenon of Entanglement

It is my aim to compare the conceptual and historical paths that led Bohr and Schrödinger to develop their positions with regard to the phenomenon of entanglement. For this purpose, the concept of holism and non-separability in relation to the views of Bohr and Schrödinger will be crucial for reconstructing their standpoints. The idea will be upheld that the concept of non-separability underlies the phenomenon of entanglement. Furthermore, I shall place emphasis on the divergences between Bohr and Schrödinger in spite of their shared holistic world view.

Keywords: Entanglement · Holism · Non-separability · Bohr · Schrödinger.

El aspecto holístico del fenómeno del entrelazamiento

Mi es objetivo comparar los caminos conceptuales e históricos que llevaron a Bohr y Schrödinger a desarrollar sus posiciones con relación al fenómeno de entrelazamiento. Para este propósito, el concepto de holismo y no separabilidad en relación a las opiniones de Bohr y Schrödinger serán cruciales para reconstruir sus posiciones. La idea será sostener que el concepto de no separabilidad subyace en el fenómeno de entrelazamiento. Todavía más, pondré el énfasis en las divergencias entre Bohr y Schrödinger a pesar de su compartida visión holista del mundo.

Palabras Clave: Entrelazamiento · Holismo · No separabilidad · Bohr · Schrödinger.

ROBERTO ANGELONI was a Marie Curie fellow at the University of Paris Diderot, France, after being awarded the prestigious Marie Skłodowska Curie fellowship. Since his PhD’s completion (University of Cagliari, Italy, 2011), Roberto Angeloni has organized several international workshops and seminars; he has participated in numerous international conferences, and has published two books and several papers in the field of the history and philosophy of science and history of physics. Angeloni’s research interests range over a great variety of themes: from the foundations of quantum theory to the history of contemporary philosophy, with particular regard to the neo–Kantian School of Marburg and the history of the philosophy of science in the twentieth century.

INFORMACIÓN DE CONTACTO | CONTACT INFORMATION: Via Andrea Vesalio, 18, 09134, Cagliari, Italy. e-mail (✉): robert_angeloni@hotmail.com · iD: http://orcid.org/0000-0003-1173-3309

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