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Research Article

AN INTRODUCTION TO THE EMERGING DYNAMICAL DUAL PARADIGM IN CONTEMPORARY QUANTUM BIOLOGY AND ITS ONTOLOGICAL IMPLICATIONS

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A R T I C L E I N F O

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A B S T R A C T

This Short Communication we will introduce the emerging dynamical dual paradigm in contemporary quantum biology, where information appears as a fundamental physical magnitude just like matter-energy. Its main ontological implications will be presented as well.

INTRODUCTION

Over the last decades we have witnessed a paradigm shift in the context of life sciences, focused on a dynamical interpretation of the fundamental notion of bioinformation (Zenil, 2012, 2017; Walker *et al*., 2017; Zenil*et al*., 2017; Zenil *et al*., 2018). This notion integrates the semantic aspect of biological information that was previously missing (Küppers, 1996; Küppers, 2010). Simplifying, there are two orders of determining factors at the basis of this paradigm shift:

Internal factors. a) Refutation of molecular biology's Central Dogma (CD): until the '90s CD was the "normal" theoretical framework for the explanation of the flow of genetic information between the three major families of information-carrying biopolymers, DNA, RNA and proteins. CD treats bioinformation as a mere sequential, "syntactic" information (Crick, 1970). b) Genetics drops its guiding role: in the concrete practice of biological research this happens because of a) theoretical advances in biophysical modelling of bioinformation[1] (Fröhlich, 1968; Del Giudice *et al*., 1983, 1984,2009; Marchettini *et al*., 2010); b) developments of sequencing technologies and other bioinformatic technologies for the gene/protein prediction (Attwood *et al*., 2011) and of optogenetic interfaces (Deisseroth, 2015). These technologies increase the recognition of the role played by epigenetic factors and inscribed modular genetics methods in a multidisciplinary research context for cell-type targeting, respectively.

External factors. Theoretical developments of structural sciences, i.e. information theory, systems theory, complexity theory, network theory, which are the main sources for the mathematical modelling of life sciences (Küppers, 2000).

A dynamical model for the semantic bioinformation has been popularized by the Copenhagen-Tartu school of biosemiotics (Deacon, 2008a,b, 2010, 2011; Kull *et al*., 2009). However, more rigorous advancements come from the information theoretic approach to quantum biology[2]. Since the '80s works on Umezawa's thermal field dynamics, understood as quantum field dynamics within the theoretical framework of thermal Quantum Field Theory (QFT), have achieved an effective modelling of bioinformation's micro-physical basis: biological systems are viewed as the realization of a living "phase", i.e. a dynamical state of matter (Vitiello, 2010). The emerging properties of the system depend on the global dynamics of interactions between the elementary constituents and are controlled by order parameters, e.g. by temperature.

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[1]It is well known that the German physician Schrödinger was the first to apply the thermodynamical physical concept of information to the basic living system of the cell. Schrödinger's "neghentropy" was then supplemented by other formulations, i.e. "syntropy" and "biological organization", which underline the aspect of "self-organization" that is central for the understanding of the dissipative structures far from thermodynamic equilibrium of biological systems. Notwithstanding Szent-György's pioneering attempt of a quantum approach to bioinformation, it is only with Del Giudice and Frölich's works that one has a first systematical understanding of the fundamental quantum order of biological organization.

[2]See (Fields, 2012; Goyal, 2012; Zenil, 2013) for an updated survey of the information theoretic approach to quantum physics.

In this Short Communication we will introduce the emerging dynamical dual paradigm in contemporary quantum biology and its main ontological implications.

DISCUSSION

Thermal QFT does not interpret the duality wave-particle related to the Heisenberg uncertainty principle as a duality between two “representations” of the phenomenon that depend on a measurement operation-as it is well known, in the classical Quantum Mechanics interpretation of the principle, the uncertainty is on the position or on the momentum of the particle. The duality relationship is between two dynamical entities, the force field and the associated quantum particles, that are viewed as the quanta of the associated field different for different types of particles. Actually, according to the thermal QFT’s interpretation of the principle, uncertainty is on the number of quanta of force field or on the field phase. This interpretation of the wave-particle duality as a force field-quantum particles duality is strictly connected to two principles, that are distinctive of the thermal QFT:the principle of Dynamical Spontaneous Symmetry Breaking (DSSB) of the Quantum Vacuum (QV)and the Doubling of Degrees of Freedom (DDF) principle.

From the universal dynamic substratum of the QV, which is intuitively a sort of disordered continuum of oscillating fields[3], all the particles and all their systems emerge dynamically as many Spontaneous Symmetry Breakdowns (SSBs) of the QV at its ground state, without any input from the outside. The SSB principle strictly relates to the Goldstone Theorem. According to it, each SSB corresponds to a local phase coherence domain among some oscillating fields of the QV, so as to constitute one only dynamic system with the relative particles, while freeing, at the same time, some energy from the QV bounded energy reservoir, producing some physical work. In the relativistic quantum physics, the phase velocity propagation is practically instantaneous, and doesnot depend on the physical signal propagation, so that the latter is “channeled” by the former. Indeed, in the relativistic realm (special relativity) of QFT, the phase velocity propagation, v_P, in a field phase coherence domain, is definedas $v_P = E / p$, where E is the energy of the field and p is the momentum. Therefore, in quantum entanglement phenomena, we are faced with no sending of material signals at a superluminal velocity $(v>c)$. That is, always $v \ll c$ as special relativity requires. Now, if $E = mc^2, p = mv,$ and γ is the Lorenz constant, the value of v_P is given by this simple dimensional equation:

$$v_P = \frac{E}{p} = \frac{\gamma mc^2}{\gamma mv} = \frac{c^2}{v}$$

When we recall that the characteristic lengths in quantum atomic physics are of the order of 10^{-8} cm, i.e., the diameter of an atom, it is evident that the phase propagation velocity is practically instantaneous.

Analogously, in the QV, each SSB corresponds to a phase coherent mode of oscillation of some of the force fields, that “breaks” the QV symmetry. Indeed, at the ground state, no phase-coherence in principle exists in the QV, where all the fields oscillate in whichever mode, and then where the entropy is maximal, or no free-energy is available, as the Second Principle of Thermodynamics requires.

The quanta of the coherent modes of field oscillations, necessarily appearing in the equations, and experimentally observed and measured, are another type of bosons, the so-called Nambu-Goldstone bosons (NGB). NGB are a new type of bosons, because, despite following the same statistic distribution of the gauge bosons of the fundamental forces, nevertheless they don’t mediate any energy exchange. Indeed, NGB are quanta of the phase coherent modes of any force field, either of interaction force fields, or of material force fields. Roughly speaking, they are not quanta of energy, but quanta of information, and for this strange nature are defined “quasi-particles” in literature. In fact, NGB have a very small mass - or they are even massless-, and then they vanish without residuals and without violating the First Law of Thermodynamics when the dynamic system they are ordering is destroyed. In other terms, their condensation does not imply a change of the energy state of the system.NGB take different names according to the different force fields of which they control, by channeling the energy exchanges, the possible coherent modes of stable interaction. So, in the organic matter and in water-in which only the biological molecules are active-, the complex structures of the bio-moleculesand the ordered sequences of chemical reactions constituting each single biological complex functionare ultimately derived by NGB named polarons (Fröhlich, 1968; Del Giudice *et al*., 1983, 1984,2009; Marchettini *et al*., 2010). In fact, what characterizes these molecules of water and organic matter is a strong electrical dipole field[4].

In a dissipative, open model of the thermal QFT that deals with biological systems, the DDF principle controls the behavior of electrically polarized biomolecules and water molecules assemblies, whose rotational symmetry is “broken down” - they are orientated into one only direction (see Fig. 1). The macroscopic bodies, constituted by “condensations” of the elementary constituents (molecules, atoms, quarks and leptons, etc.), are depending on as many “phase coherences” or coherent modes of oscillation of the relative force fields, determining the long-range quantum entanglements, and hence the macroscopic unity of each body, as well as their reciprocal differences. The DSSB of the QV ensures the definition of an optimal dynamic channeling for the successive propagation of the energy added to system from its thermal bath: this explains the emergency of a long rage coherent domain (dynamic order), mediated by the polarons. Since QFT systems are always in interaction with the background fluctuations (quantum vacuum condition), biological systems are recognized as intrinsically open thermal systems also at the quantum level.

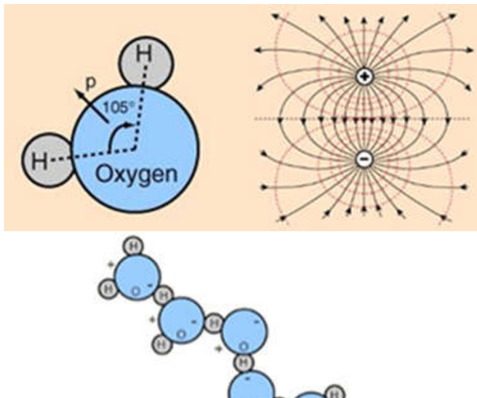

Fig 1 Asymmetric structure of the water molecule with the direction of the dipole momentum p pointing toward the more positive H atoms, that creates a positive charge. (Center) The electric potential of a dipole (black lines) show a mirror symmetry about the center point of the dipole. The dipole electric field lines are everywhere perpendicular to the electric field lines (dotted red lines). (Right) Water molecular bond is depending on the dipole momentum, because of the asymmetric distribution of the dipole charges in each. Images are from the item “Electric Dipole” in the educational site

[3]The association of any mole of matter with a force field, and therefore the existence of the QV as the totality of the quantum force fields, is an immediate consequence of the Third Law of Thermodynamics and, in this sense, QFT ultimately is a thermal field theory (Blasone et al., 2011, p. ix).

[4] As it is well known, indeed, in a water molecule the two atoms of hydrogen, with their positive electromagnetic charges, are located both on the same side of the oxygen atom, so as to determine a dipole field. See Fig. 1.

"Hyperphysics", hosted by the Dept. of Physics and Astronomy at the Georgia State University (URL: < http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html >).

To offer a more satisfying theoretical picture of this crucial point, it is essential to keep in mind that in dissipative QFT the classical Stone-Von Neumann Theorem does not hold (Vitiello, 2007, p. 2). This theorem states that, for system with a finite number of degrees of freedom, which is always the case in Quantum Mechanics because of the man-made choice by the observer of the orthonormal finite basis of the Hilbert space for representing a quantum system, the representations of the canonical commutation relations are all unitarily equivalent as to each other. On the contrary, in QFT systems, because we are faced with infinitely many phase transitions, the number of the degrees of freedom is not finite, so that infinitely many unitarily inequivalent representations of the canonical commutation (bosons) and anti-commutation (fermions) relations exist, as the fundamental Haag's Theorem demonstrated in the late 50's of the last century (Earman and Fraser, 2006). This holds not only in the relativistic (microscopic) domain, but it applies also to non-relativistic many-body systems in condensed matter physics, i.e., in the macroscopic and even in the cosmological domain, through the Principleof the QV Foliation at the ground state (Blasone *et al*., 2011, pp. 53−96). That is, different SSBs and hence phase coherence domains at the QV ground state can be "stratified" over each other, so as to originate the so-called complex physical systems. The Principle of the QV Foliation is a "robust principle of construction and of memory used by nature for generating ever more complex systems" (Basti *et al*., 2017, p. 39). It is important to recall the role played by the notion of stored energy in such a multi-level organization in coherent domains and sub-domains. Indeed, "this completes the classical thermodynamic picture of L. Szilard and L. Brillouin according to which the 'Maxwell demon', for getting information so as to compensate the entropic decay of the living body, must consume free energy from the environment. This means an increasing of the global entropy according to the dictate of the Second Law. However, this has to be completed in QFT with the evidence coming from the Third Law" (Basti, 2017, pp. 181−182).

Formally, thermal QFT provides a systematic use of the dual categories of q-deformed Hopf coalgebras and algebras, characterized by non-commutative products and coproducts because of the thermal parameter linked to the angle of the Bogoliubov transformation, mapping operators of particle creation-annihilation. q-deformed Hopf coalgebras and algebras constitute a category - in the category theoretic sense[5]- because any algebra can be seen as a structure defined on sets, characterized by an endofunctor projecting all the possible combinations of the subsets of the carrier set, on which the algebra is defined, onto the set itself. On the other hand, any coalgebra can be seen as a structure defined on sets, whose endofunctor projects from the carrier set onto the coproducts of this same set. The DDF principle provides a coalgebraic "doubling" of the algebras, so to model an open quantum system: the systemand its mirroring thermal bath. Of course, because of the energy balance condition - of the system with its thermal bath -, open quantum systems recover the classical Hamiltonian character. Recently, a mathematical and logical dual equivalence between the categories of q-deformed Hopf coalgebras and algebras in QFT has been demonstrated within the theoretical framework of CT(Basti *et al*., 2017): it is induced by the contravariant functorrelated to the Bogoliubov transform. The necessity of such a contravariance depends properly on the constraint of satisfying anyway the energy balance principle.

Now, it is well known that the representation theory of a Hopf algebra is particularly nice, especially the topological one that we will stress in the following. In the special case we are dealing with, the topological representation on the category Hilbert of Hilbert spaces is associated via the so-called Gelfand-Naimark-Segal constructions with the topological representation on the category Stone of Stone spaces, which represents Boolean algebras according to the fundamental Stone representation theorem. In the thermal interpretation of topological QFT the topological orders do not define a Hilbert sub-space of degenerated states of the system, but a doubling of the states in accordance with the DDF principle: the definition and the measure of the minimum free energy function become an intrinsic dynamical tool of choice among states, so as to grant a dynamic determination of the orthonormal basis of the Hilbert space. The association between Hilbert and Stone ensures a semantic content for the physical information linked to the minimum free energy function (Basti *et al*., 2017). Of course, the probability measures associated with the thermal interpretation of QFT are related with the Wigner function defined on the phase space of the system: the Wigner function uses the notion of quasi-probability, and not the notion of probability of the classical Kolmogorov axiomatic theory of probability (Basti, 2017, § 2.3).

On Stone one represents also the modal duality between MBAlg, the category of modal Boolean algebras, and Stone-Coalg, the category of Stone coalgebras that are the topological counterparts of the coalgebras defined on Aczel's Non-Well-Founded sets for the power set endofunctor (Kupke *et al*., 2004). For our aims the most relevant point here is that Modal Logic (ML), meant as the proper logic of Stone coalgebras, has a finitary universe that is computable effectively. This is a very important result: it opens indeed an interdisciplinary partnership between theoretical physicians and theoretical computer scientists focused on the topic of a dynamical interpretation of the topological quantum computing within a new coalgebraic universality (Properzi, 2018). Since ML is a main formal tool of philosophical logics, it is natural that the partnership extends also to philosopher.

In general, because of the systematic application of the CT formalism in fundamental physics, there have been recent significant attempts to re-orient the debate on the Structural Realism (SR) from a set theoretic to a category theoretic formulation of structure and object (Bain, 2013). Focusing on its onticversion, the debate concerns the ontological status of relational objects, assuming the fact that for an ontic structural realist what exists in the physical realm are, at least primary, structures. In this general debate the eliminative ontic structural realists oppose the non-eliminative ones. Within the framework of CT, the main version of the Ontic Structural Realism (OSR) till now proposed is Lyre's Humean one (Lyre, 2009, 2010, 2012): this is a moderate non-eliminative OSR, according to which only relational properties and structurally derived intrinsic properties of *relata* exist. Lyre's categorial understanding of structures is thought of as a non-dispositional and non-essential type. As such, it opposes the causal and the modal accounts of physical structures, whose proponents are, *interalia*, Chakravartty and Esfeld, respectively (Chakravartty 2007; Esfeld 2009, 2013; Esfeldand Lam, 2011, 2012).

However, considering the ontological implications of the paradigm shift that has been sketched in this Communication, the categorial understanding of structures is reconcilable with the causal and modal ones. Indeed, following Dodig-Crnkovic and Basti's works (Basti 2016; Dodig-Crnkovic 2016, 2017a,b), it is possible to develop a new dual approach to the categorial structural realism: the so-called

[5]The fundamental notion of Category Theory (CT) is that of "arrow" or "morphism": objects corresponding in CT to identity morphisms, i.e., reflexive morphisms whose domain and codomain coincide, so that they do not constitute a primitive of the theory. Actually, CT's primitive notions are such: 1) "morphism" or "arrow", namely the orientated relation that generalizes logical and mathematical notions such as "predicate", "function", "operator"; 2) "domain-codomain", that is the map that assigns to the relation a direction from a source (domain) to a target (codomain), making it a morphism or arrow; 3) "morphisms composition", i.e., two or more morphisms are arranged in a sequence to form a new morphism (Abramsky and Tzevelekos, 2011). So, broadly speaking, CT's categories are not predicative, but relational categories: a relational category is any collection of morphisms, compositions of morphisms and objects, i.e., identity (reflexive) morphisms, that preserves the structure up to isomorphism. "functor" is the operation mapping objects and arrows of a category into another category. In other terms, it is a morphism between categories that preserve compositions and identities, so that between the two categories there exists a homomorphism up to isomorphism. Generally, a functor is covariant, that is, it preserves arrows directions and composition orders. Even if a functor connecting two categories is contravariant, i.e., reverses all the arrows directions, and all the composition orders, the categories are homomorphic up to isomorphism.

Infocomputationalism (ICON). ICON integrates (Floridi's 2008) Informational Structural Realism through a categorial account of both material and informational physical structures. It detects two abstract dual structures, i.e., matter-energy/information, on the one hand, and information/computation, on the other hand. Information is thus seen as a fundamental physical magnitude just like matter-energy, and dynamics is reframed as a computation performed by nature itself. According to ICON, the physical information constantly flows along the increasingly complexity of the natural structural levels, regardless of the mind activity. The synthetic habitus of the mind, that according to Lyre underpins the physical structures, appears, instead, as an emerging level of the physical information embodied in the underlying brain dynamics. A formal account of ICON's dual ontology of quantum physics is provided by the duality between MBAlg and Stone-Coalg, that is the same modal duality that allows us to interpret the maximal entropy in a thermal QFT system as a semantic measure of information. Causes and modalities lie at the very "core" of the physical categorial structures.

Conflicts of Interest*:* The author declares no conflict of interest.

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