**FACTA UNIVERSITATIS**
Series: **Physics, Chemistry and Technology** Vol. 13, N$^o$ 1, 2015, pp. 29 - 38
DOI: 10.2298/FUPCT1501029J

# ON INDIVIDUALITY IN QUANTUM THEORY

*UDC 530.145*

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**Abstract**. *A quantum mechanical analysis of the decomposability of quantum systems into subsystems provides support for the so-called "attenuated Eliminative Ontic Structural Realism" within Categorical Structuralism studies in physics. Quantum subsystems are recognized as non-individual, relationally defined objects that deflate or relax some standard objections against Eliminative Ontic Structural Realism. Our considerations assume the universally valid quantum theory without tackling interpretational issues.*

**Key words**: *composite quantum systems, individuality, categorical structuralism, Eliminative Ontic Structural Realism*

## 1. INTRODUCTION

"*In particular, one issue which has been often taken for granted is looming big, as a foundation of the whole decoherence program. It is the question of what are the 'systems' which play such a crucial role in all the discussions of the emergent classicality. (. . .) [A] compelling explanation of what are the systems – how to define them given, say, the overall Hamiltonian in some suitably large Hilbert space – would be undoubtedly most useful*." (Zurek, 1998).

Arguably most of practicing physicists believe in some kind of individuality of quantum systems they investigate. In classical physics, "systems" are apparently individuals: "*Everyday objects like chairs, houses, and bicycles are commonly held to be individuals in that we can refer to them with singular terms (we can name them, or refer to them with indexical expressions or definite descriptions) and meaningfully compare them to other objects*." (Frigg and Votsis, 2011). However, in quantum mechanics, the notion of "individual" becomes problematic for several reasons. On one hand, linearity of quantum dynamics (Schrodinger law) implies quantum entanglement, which suspends the basic classical-physics assumption that subsystems have the states of their own. Entangled systems cannot be described by their own independent quantum states-quantum non-

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Received November 8th, 2014; accepted January 12th, 2015.

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separability (D'Espagnat, 1999). On the other hand, statistical nature of quantum processes conceals individual characteristics of single elements of a quantum ensemble represented by "density matrix" (pure or mixed quantum states) - not even to mention indistinguishable particles.

There is yet another aspect of challenging individuality of quantum systems of universal interest: investigation of decomposition of a quantum system into subsystems ("quantum structures") (Jeknić-Dugić et al., 2013a and references therein). In this paper we address the topic of Quantum Structures (QS) – which in the context of decoherence theory is fairly described by the above quote from (Zurek, 1998) – and place the topic in the context of Category Structures studies, (e.g., Frigg and Votsis, 2011; Muller, 1998). In this paper we do not tackle interpretational issues and ramifications.

Quantum structure studies start with an assumption on existence of physical subsystems and come at the point shared by Categorical structural studies on secondary role of "objects", without making a reference to interpretations of quantum theory. In Section 2 we offer a survey of "quantum structures" topics and issues. In Section 3 we give our main results regarding both epistemic and ontic contexts of the quantum structures studies. Quantum subsystems appear as a kind of non-individual relationally defined objects. Section 4 is conclusion.

## 2. QUANTUM STRUCTURE: A SURVEY

Quantum mechanics offers a striking and counterintuitive observation: typically, there is more uncertainty about quantum subsystems than about the total system composed of the subsystems (Nielsen and Chuang, 2000).

In classical physics, "structure" (decomposition into subsystems) is pre-defined and assumed foundational-the bottom-up reductionistic description of physical systems. Variations of structure of a classical system thus appear as mathematical procedures without physical contents – mathematical artifacts. However, structural variations in quantum theory may not share the classical prejudice and intuition. Sometimes it is easier to observe the center-of-mass position e.g. of Brownian particle or the relative position than the constituent particles positions (Rau et al., 2003; Knott et al., 2013), while it is also possible to manipulate and even engineer "virtual particles" in certain setups (Jurcevic et al., 2014).

Probably the most often used structural transformations are: (1) decomposing a system into smaller parts (subsystems) that provides reducibility of one to another structure of a composite system; (2) grouping the systems as the inverse to (1), e.g. clustering in the many-body scattering (Jeknić-Dugić et al., 2014a and references therein); and (3) introduction of the center-of-mass and internal (relative) degrees of freedom. All those transformations which include introduction of the most of "virtual" quantum particles can be described by Linear Canonical Transformations (LCTs) that induce different tensor-product-structures (TPSs) of the composite system's Hilbert state space $H$.

Investigating the different TPSs (typically bipartitions) constitutes the core of the Quantum Structure studies (Jeknić-Dugić et al., 2013a and references therein). The universal character of quantum formalism provides a basis for at least formally equal treatment of different structures of a composite quantum system, in contrast to the classical prejudice and reductionistic intuition. Therefore, we can say that QS studies constitute *a top-down approach* to quantum structures of universal character for open or closed, finite-or infinite-dimensional systems.

Paradigmatic is the model of the simplest composite system of the hydrogen atom. Fundamentally, the hydrogen atom is defined as a pair of quantum particles, "electron + proton" $e + p$. However, quantum theory and most of the phenomenology of the hydrogen atom distinguishes the alternative structure, "center of mass + relative particle" ($CM + R$). An instantaneous state, $|\Psi\rangle$ of the atom (neglecting the particles' spin) (Jeknić-Dugić et al., 2013a; De la Torre et al., 2010; Jeknić-Dugić et al., 2014b):

$$|\chi\rangle_{CM} \otimes |nlm\rangle_R = |\Psi\rangle = \sum_i c_i |i\rangle_e \otimes |i\rangle_p \tag{1}$$

In eq. (1): $n$, $l$, $m$ represent the well-known quantum numbers from the standard quantum theory of hydrogen atom. Eq.(1) is adapted to the different factorizations (structures) of the Hilbert state space:

$$H_{CM} \otimes H_R = H = H_e \otimes H_p \tag{2}$$

Notice that the two structures of the atom, $S_1 = \{e, p\}$ and $S_2 = \{CM, R\}$, are mutually irreducible: e.g. one cannot break the *CM* system in order to find either *e* or *p in* the *CM* system. The transition from the $S_1$ to the $S_2$ structure:

$$\vec{R}_{CM} = (m_e\vec{r}_e + m_p\vec{r}_p)/(m_e + m_p),\ \vec{\rho}_R = \vec{r}_e - \vec{r}_p \tag{3}$$

is not obtained via grouping or decomposing. Furthermore, the pairs $\{e, p\}$ and $\{CM, R\}$ represent the pairs of mutually irreducible "elementary particles" for the pertaining structures, $S_1$ and $S_2$, of the single quantum system called "hydrogen atom".

Quantum structures studies consider "atom" as a (total, composite) system with different facets defined by the possible structures: "atom" = "electron+proton" = "center of mass + relative particle". So the concept of "subsystem" is relative, i.e. structure-dependent in the sense that the different tensor-factorizations eq.(2) define different local systems (subsystems) and the pertaining local actions (operations) - the LOCCs in quantum communication theory (Nielsen and Chuang, 2000).

Due to eq.(2), the atomic Hamiltonian $\hat{H}$ obtains different forms for the two structures:

$$\hat{H}_e \otimes \hat{I}_p + \hat{I}_e \otimes \hat{H}_p + \hat{H}_{\text{int}} = \hat{H} = \hat{H}_{CM} \otimes \hat{I}_R + \hat{I}_{CM} \otimes \hat{H}_R \tag{4}$$

In eq.(4) there appear the self-Hamiltonians for the atomic subsystems while $\hat{H}_{\text{int}}$ is the Coulomb interaction for the ($e$, $p$) pair.

The "identity" operators, $\hat{I}$, emphasize local operators. For instance, the electronic self-Hamiltonian, $\hat{H}_e$, does not act on the proton's state space, $H_p$, and is therefore written as $\hat{H}_e \otimes \hat{I}_p$. However, this locality is relative, i.e. applicable *only* for the $e + p$ atomic structure. Regarding the alternate $CM + R$ structure, all electron's and proton's observables are "collective", and *vice versa*. Physically, from eq.(3), measurements performed on *e* simultaneously tackle both *CM* and *R* but only partially—the proton's degrees of freedom remain intact. Needless to say, simultaneous actions on both *e* and *p* are the actions on the total system - the hydrogen atom as a whole - and are equivalent with the proper actions performed simultaneously on both *CM* and *R*.

This relativity of "system" (i.e. of "subsystem") and locality (which does not assume relativistic locality) of operations are basic for the quantum structures studies for open as well as for closed, finite- or infinite-dimensional quantum systems.

Eq.(1) is an instance of Entanglement Relativity, which has been discovered and rediscovered in the last ten years approximately (De la Torre et al., 2010; Ciancio et al., 2006; Dugić and Jeknić, 2006). Mathematically, Entanglement Relativity establishes non-preservation of quantum entanglement by LCTs as well as the following finding: there is entanglement for every quantum state of a composite system. Virtually every structural change gives rise to a change in the amount of entanglement. Moreover, relativity of correlations also applies for mixed states, i.e. for open quantum systems described by the density matrices $\hat{\rho}$ ($\hat{\rho}^2 = \hat{\rho}$). It can be shown (Dugić et al., 2013) that "quantum discord" (which quantifies non-classical (quantum) correlations for bipartitions of open quantum systems) is also relative. Hence a new universal rule of the universally valid quantum theory: virtually every change in structure (induced change in TPS) provides a change in the amount of correlations in bipartitions of the composite quantum systems - Quantum Correlations Relativity (Dugić et al., 2013). In effect, quantum information resources implemented by non-classical correlations are *ubiquitous*. Thus the very basic concepts of "subsystem", "correlations" and "locality" are *not* characteristic for a composite system in so far as they are typical of the system's *structure*. So, saying that there are correlations in a composite system does not *per se* make sense; such a statement must be accompanied by distinguishing the structure it refers to. E.g. saying that there is no correlation in the hydrogen atom is correct for the $CM + R$ but not for the $e + p$ structure, eq.(1). It is now obvious: all the correlations-related physical observations such as those for information processing (Nielsen and Chuang, 2000), quantum phase transitions (Sachdev, 2006; Wichterich, 2011) or thermalization (Del Rio et al., 2014) are relative, i.e. structure-dependent.

The open quantum systems theory (Breuer and Petruccione, 2002; Rivas and Huelga, 2011) describes the atomic (and molecular) species as open quantum systems (Jeknić-Dugić et al., 2014b; Breuer and Petruccione, 2002; Rivas and Huelga, 2011). The open system's theory answers the question of existence of preferred structure of realistic physical systems. The quantum vacuum fluctuations monitor the atomic *R* system and so promote the $CM + R$ structure as the preferred, directly accessible atomic structure while both the *CM* and *R* systems have the definite quantum states - the l.h.s. of eq.(1). The atomic $e + p$ structure is not chosen by the vacuum fluctuations and, due to eq.(3), manipulating the atomic electron (proton) requires actions partially exerted on both the atomic *CM* and R subsystems.

Environmentally chosen preferred structure of an open system is a tacit assumption of the whole of decoherence program (Schlosshauer, 2004). Only a special set of the degrees of freedom of a composite system are monitored and decohered by the environment. E.g. the center-of-mass of the Brownian particle is monitored by solvent molecules (Breuer and Petruccione, 2002 and references therein). The particle's internal degrees of freedom are typically assumed to remain intact by the solution the particle is suspended in. However, this plausible physical picture is notoriously hard to be derived from the microscopic models in full generality. Only for the comparatively simple models (Stokes et al., 2012; Arsenijević et al., 2013; Lee et al., 2014) can one justify this conjecture of substantial role of the environment. Needless to say, the subsystems of the preferred structure are typically directly accessible (Zanardi, 2001) to an observer who learns about the structure and behavior of the total (composite) open system.

On the other hand, as there is no observer to the Universe as a whole, existence of the Universe preferred structure remains unanswered. As yet, one has to admit the absence of any universally adopted rule. For the choice of the preferred universal structure, see the next section and (Roberts, 2011) for a similar point of view, and (e.g. Dieke, 1998) for the opposite point of view.

## 3. QUANTUM STRUCTURE IN CONTEXT OF CATEGORICAL STRUCTURALISM

Quantum structures studies start from the standard prejudice of the existence of quantum systems and come at the conclusion on the relativity of "quantum system". This is the relativity of "objects" in the sense of category studies. The relativity of "system" can be discarded on the level of interpretation of quantum theory, e.g. in Bohm's theory, which is not our concern.

Quantum structures studies provide different facets of composite quantum systems and therefore a basis for their emergent behavior (Wallace, 2012). However, emergent behavior is not without limitation. Regarding local systems (subsystems), the fundamental role of the environment is found. Typically, there is a preferred structure of a composite open system (Stokes et al., 2012; Arsenijević et al., 2013; Lee et al., 2014). On the other hand, for certain models of isolated (closed) quantum systems, notably the quantum Brownian motion, there exist mutually irreducible structures (Dugić and Jeknić-Dugić, 2012) for which it is not clear how a reasonable physical "emergent model" is constructed (Jeknić-Dugić et al., 2014c).

Quantum structures studies provide a striking observation: regarding the Universe as a whole, there is more than one set of fundamental constituents. This observation stems from the observation that certain structures are mutually irreducible structures (Dugić and Jeknić-Dugić, 2012). Without an *a priori* rule or a postulate (e.g. interpretational rule of the Bohm's theory), one cannot discriminate between the sets of "elementary particles" for mutually irreducible structures. "*Without further physical assumption, no partition has an ontologically superior status with respect to any other*" (Zanardi, 2001), but also *"for many macroscopic systems and, in particular, for the universe as a whole, there may be no natural split into distinguished subsystems and the rest, and another way of identifying the naturally decoherent variables is required*" (Halliwell, 2010).

On the face of this observation, one may go even further and say that "there are no particles" - wisdom so natural in the context of quantum decoherence (Zeh, 1993). In the CS studies vocabulary, this reads: "there are no objects". On the other hand, operational quantum information clearly distinguishes physical reality of correlations which constitute the basic quantum information resource (Nielsen and Chuang, 2000). Furthermore, the so-called device-independent quantum information processing conjures "substrate independence" for quantum information processing. The emphasis is on an abstract mathematical analysis of probability space with the view of the possible post-quantum theory and foundational issues of relativistic locality and causality.

It seems that giving the secondary importance to "quantum system" ("object", "relata") is a tacit and not-yet-fully recognized salient characteristic of modern methods of quantum theory. Regarding QS studies based on the linear-canonical-transformations-induced tensor-product structures (see Section 2), this can be performed according to the most common set-theoretic basis of Category Structure studies.

### 3.1. Epistemological aspects

Undeniably, quantum mechanics is mainly about putting in order information acquired by "quantum measurement". In this paper we refer to quantum measurement as a phenomenological fact based on perception and empirical generalizations that are mathematically encapsulated by quantum theory such are the expressions in Section 2. We are not interested in the interpretation of quantum theory and the so-called "measurement problem" or in reducing quantum theory merely to acquiring information (Caves et al., 2002), nor do we tackle possible extensions of the standard theory (e.g. Jeknić-Dugić et al., 2014a; Ghirardi et al., 1986; Kafri et al., 2014) that remain out of the present considerations.

Every interaction produces correlations for interacting systems. Physical (classical or quantum) correlations implement "structure" in the sense of Categorical Structuralism. Acquiring information for an observer is performed via the use of correlations. Even manipulations aimed at maximizing the success of the quantum information protocols can often be described purely in the sense of CS structure ("relations") without even mentioning “relata” (physical systems).

For instance, in quantum teleportation (Bennett et al., 1994), a set of three quibts, $C = 1 + 2 + 3$ can be differently decomposed. The initial state:

$$\begin{aligned} &|\chi\rangle_1 \otimes |\Psi^-\rangle_{23} = (|\Psi^-\rangle_{12} \otimes |u_1\rangle_3 + |\Psi^+\rangle_{12} \otimes |u_2\rangle_3 + \\ &|\Phi^-\rangle_{12} \otimes |u_3\rangle_3 + |\Phi^+\rangle_{12}^{E} \otimes |u_4\rangle_4)/2 \end{aligned} \tag{5}$$

In eq.(5), $\{|\Psi^\pm\rangle, |\Phi\pm\rangle\}$ constitutes the so-called Bell-states orthonormalized basis, with non-orthogonal $|u_i\rangle$ states.

The structures of the $C$ system appearing in eq.(5) are obtained via grouping the qubits $1 + (2 + 3) \rightarrow (1 + 2) + 3$, again exhibiting Entanglement Relativity, i.e. entanglement monogamy through the "entanglement swapping" procedure. Quantum teleportation is possible due to the choice of measurement pertaining to the total system's $(1 + 2) + 3$ structure and employs quantum entanglement present on the r.h.s. of eq.(5) as "quantum channel" for teleportation. There is not any direct manipulation with qubits. Just like eq.(1), the expression eq.(5) refers to an instantaneous, fixed state of the total system. No real transformation on the system and its state or even qubits exchange has been performed.

Entanglement relativity is used as a resource for transferring information from the 1 to the qubit *3*, with the use of the local unitary operation and measurement on the qubit 3 as the final step in the teleportation. Local operations adapted to the structures of interest are performed in the initial (preparation) stage and in the final stage of the protocol. The carriers of teleportation are exclusively quantum correlations (entanglement) between the supposed objects, which, in turn, are not involved in the intermediate stages of the protocol.

Indeed, the agents take care about the objects' relations as the quantum information resources in the quantum information protocols and algorithms. The objects (quantum systems, qubits) are of secondary importance and are only implicitly present through the definition of quantum measurements that should be performed.

In the spirit of Ramsey Sentence (Ramsey, 1931), an agent capable of operationally confirming e.g. the l.h.s of eq.(1) should be convinced of the validity of the r.h.s of eq.(1) without a doubt. Equality present in eq.(1) is a mathematical truth that guarantees reliability of all conclusions derived from both sides of eq.(1). On the face of this and discussion in Section 2, if the domain of the categorical structure for the composite system *C* are all the possible TPSs, the agent can hardly express his/her findings in terms of objects (subsystems of the *C* system). In order to make a sensible expression in the terms of objects, the domain should be reduced to only one TPS. This, of course, requires some prior knowledge or at least a hypothesis about the composite system's structure. At this point we recognize a need for transmissibility (Quine, 1968). Finally, predictive power of mathematical expressions like eq.(1) or eq.(5) goes hand in hand with the argument of (Votsis, 2004): as long as mathematical expressions "coincide" with experimental observations, we neither need to worry about the alternative structures reality nor should we worry about the alternative-structures-subsystems physical nature. Mathematical predictions serve their operational purposes without a necessity to refer to physical interpretation in terms of "objects". What is necessary, however, is to account for the relativity of correlations (e.g. Peres, 2000; Ma et al., 2012) without the worry that some correlations may be "artificial" (Redhead, 2001; Psillos, 2001) or that the identity of realistic objects can be decisively, experimentally established, e.g. in the sense of "entity realism" (Hacking, 1983) or "semirealism" (Chakravartty, 1998).

Our observations may sound as a FAPP (FAPP is John Bell's suggested abbreviation of "for all practical purposes"), which is not our point. Rather, our analysis is *minimalistic* in that we do not add or assume anything beyond the standard meaning of the mathematical expressions, such as those in Section 2. Hence we emphasize the secondary role of objects in the quantum structures studies that will be elaborated in the next section.

### 3.2. Ontological aspects

From the ontological point of view, Quantum Structures studies support the so-called "attenuated Eliminative OSR" (Frigg and Votsis, 2011; French and Krause, 1995).

As emphasized in Section 3.1, operationally, quantum correlations are directly manipulated, e.g. in quantum information practice, while the systems that are supposed to be operated on are often of secondary importance. This is in accord with the extreme ontic structural realism (OSR) (e.g. Bain, 2013), that is presented in (Lal and Teh, 2014) as follows:

"*It is coherent to have an ontology of (physical) relations without admitting an ontology of (physical) relata between which these relations hold*."

In QS studies, the existence of "objects" (physically subsystems) is not *a priori* discarded. Quantum "objects" do not possess classical individuality but can be considered objective in the *relational* sense. Regarding the hydrogen atom (Section 2), the atomic electron can be considered objective only in relation to the atomic proton and *vice versa*. This is a salient lesson of QS studies, Section 2: there is not independent individuality or even existence of subsystems of a composite system. Hence quantum subsystems as a kind of *non-individual relationally defined objects*, very much in the sense of the above mentioned attenuated EOSR.

Introduction of this kind of objects discards the common criticism of EOSR regarding the lack or "relata", (e.g. Chakravartty, 1998; Busch, 2002), but for a specific price. As emphasized above, relativity of subsystems is relativity of objects (relata). There are not *a priori* objects and, if they can be considered to exist, they are neither fundamental nor unconditional. The concept of elementary (fundamental) particles is *relative* (i.e. structure-dependent) and *relational* (meaningful in relation to other particles pertaining to the same structure).

Appearance of quantum subsystems as "objects" not possessing classical individuality also rejects the problem of infinite regression in defending the EOSR position (Ladyman and Ross, 2007): a quantum structure is described by a proper set of elementary particles. The price is that "elementary particles" i.e. the "fundamental level" are relative. The structures obtained via decomposing or grouping the systems, like in eq.(5), can have common elementary particles. Multitude of such structures can lead to emergent structure(s) for open composite systems. However, mutually irreducible structures for a closed system - which exist for every composite system, e.g. eq.(1) - do not. Thus QS studies introduce the concept of physical reality with *more than one fundamental level for the Universe as a whole*, while all the levels appear *a priori* mutually equal-physically and ontologically. Moreover, this emerging physical picture is locally consistent. Local observers can learn about the structure they are a part of, including the set of the elementary particles characteristic for the structure. On this basis they can learn about all alternative structures of the Universe in a manner similar to what is discussed in Section 2.

Relativity of the fundamental level can be recognized as a counterpart of the position by Muller (Muller, 2011) in a mathematically elaborated form. Instead of one structure, i.e. only one form of a quantum state, all the structures should be simultaneously kept in mind with their sets of relationally defined elementary particles, every set being equally described by quantum theory. For an early account see (Dugić et al., 2002).

## 4. CONCLUSION

Quantum Structures studies is a typical quantum mechanical topic without necessity for interpretational elements. Therefore, it is not expectable to offer the definite answers to all basic issues of Categorical Structural studies in physical considerations. Nevertheless, they point out the importance, natural role and place of the Categorical studies in the context of nonrelativistic quantum theory.

Simultaneous decoherence for a pair of mutually irreducible structures of a model-Universe - parallel occurrence of decoherence (Dugić et al., 2012) - suggests the existence of more than one, mutually irreducible and dynamically evolving, classical worlds in the unique physical Universe. This relativity of decoherence-induced classicality (quasi-classicality) opens a new discourse in approaching the traditionally classical fields of biology, as well as social sciences and humanities. To this end and regarding the interpretational issues of quantum theory, the research is in progress and will be presented elsewhere.

**Acknowledgement**: *This work is financially supported by Ministry of Education, Science and Technological Development, Republic of Serbia, grant 171028.*

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# O INDIVIDUALNOSTI U KVANTNOJ TEORIJI

*Kvantnomehanička analiza dekompozabilnosti kvantnih sistema u podsisteme pruža podršku za takozvanu eliminativnu ontičku strukturalnu realnost, „attenuated Eliminative Ontic Structural Realism" (EOSR), u okvirima kategoričkih studija u fizici. Kvantni podsistemi se pojavljuju kao neindividualni, relacioni objekti, što umanjuje neke od postojećih primedaba na EOSR. Naša razmatranja podrazumevaju univerzalno važeću kvantnu teoriju bez dodira sa interpretacijskim pitanjima.*

Ključne reči: *složeni kvantni sistemi, individualnost, kategorički strukturalizam, eliminativna ontička strukturalna realnost*