Review of: "Quantum Entities and the Nature of Time"

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Potential competing interests: No potential competing interests to declare.

Background independent physical theories search for a fundamental theory to extract space-time as an emergent phenomena. Background depended physical theories assume a pre-existed space-time. Regarding this classification, Quantum Mechanics and General Relativity have different perspectives on the notion of space and time. General Relativity replaces Newton's absolute space and time by a relativistic dynamical merged space-time such that space and time are considered to be the same and gravity is interpreted as the manifestation of space-time geometry. Quantum Mechanics, which deals with matter and energy at the atomic scale, addresses the appearance of a fundamental theory for the construction of space-time in the context of quantum entanglement. Quantum physics of entangled quantum states (or qubits) is rich enough to encode the geometry of a space with an additional dimension. In other word, qubits generate networks with geometry in space together with an extra dimension beyond the number of dimensions which those qubits stay in. Therefore entangled quantum states are candidates of forming the space-time fabric.

Quantum Mechanics, mathematically formulated by the functional analysis of the complex Hilbert space of states, is on the basis of observables or operators corresponding to spatial positions where time is not an observable or operator. Pure states are presented by points in a particular projective space over the field of complex numbers, observables are presented by symmetric bilinear forms and mixed states are presented by positive definite observables. While timeless propositions are associated with states, superpositions and observables, the Schrodinger's equation and unitarity encode how states and observables do change such that states can change in terms of linear maps which preserves the metric. In the space-time without time orientation model, real Quantum Mechanics equipped with a multitude of complex structures is considered. However, complex numbers are applied to present the evolution of quantum states in time on the basis of the equation $i\frac{d\Psi}{dt}=H\Psi$ with respect to the Hamiltonian H. Quantum entities are always delocalized such that because of the Heisenberg uncertainty principle, quantum variables, as properties of quantum entities, cannot be known at the same time.

The letter under review focuses on the challenge of delocalization of quantum entities where quantum discontinuity generated by quantum jumps or collapsing of the wave function should be considered as a discontinuous and non-unitary aspects of the interactions between elementary particles. In this context, quantum discontinuity identifies a level of physical reality. The author addresses the importance of the nature of time in our understanding of quantum entities where the time accessible to elementary particles shall be a complex variable. In this setting, the author aims to provide a new time-mediated interpretation of the relationship between elementary particles and the spatial domain underlying the Einstein's locality to analyze quantum discontinuity of elementary particles. If we assume a complex time, then we need to accept the existence of the evolution parameter τ of the vacuum such that the dynamics of τ is determined by discontinuities associated with the particle's localization in the time domain. A quantum jump associated with the absorption of an elementary particle at a specific point A of a screen and the simultaneous cancellation of its wave function at other separate point B distant from A does not violate the Einstein' locality.

This is an interesting proposal, however, I would like to recommend the following comments which could be useful to fill some gaps. These comments address the essential role of the Theory of Computation for a better understanding of the interaction between quantum entities and space on the basis of time-mediated variables.

A- On the one hand, real numbers are classified into two separate types namely, computable numbers and non-computable numbers. A real number a is called computable if there exists a finite terminating algorithm which could approximate a in any arbitrary small neighborhood. Computable functions are applied to determine computable numbers such as rational numbers, algebraic numbers, π, ${\rm e}$,.... A complex number $z=x+iy$ is computable if x,y are computable. Theory of Computation shows that the collection of all computable numbers is infinite countable which means that, up to the Lebesgue measure, almost every real number is not computable. On the other hand, measurement process is one fundamental challenge in Quantum Mechanics where collapsing wave functions leads us to generate some definite values with respect to properties of elementary particles. Instruments can only generate computable numbers. This means that the only values assigned to quantum jumps or time-mediated parameters are computable numbers generated by a system of measurement. Therefore the first challenge is to show how the evolution of (entangled) quantum states and time-mediated parameters generate non-computable numbers. In other words, the correspondence between delocalization and real numbers is unclear and the author should clarify the existence of properties of quantum entities which might generate non-computable numbers. It is like non-computable real numbers play the role of hidden variables of a more fundamental theory for the complex model of time.

B- The payment of locality is the access to only computable real numbers. It seems that non-computable real numbers are useful to present non-local properties. The author should consider the interrelationship between dualities computable--non-computable and locality--non-locality.

C- Without using non-computable numbers, time in a quantum system with finite degrees of freedom has a discrete nature which is compatible with quantum discontinuity of elementary particles and quantum jumps. The author should searches for a theoretical model which explains the process of passing from this discrete setting to the analytic evolution of (entangled) quantum states via Schrodinger's equation and unitarity underlying a continuous model of time.

D- If we consider space-time as an emergence of quantum entanglement, then what is the time-mediated interpretation of the relationship between elementary particles and the spatial domain? What is the meaning of localization in this situation? In other words, the author should consider the impact of non-locality in his proposal.

E- The author should clarify that whether his model is valid for space-time without time orientation or not?

F- It seems that the statement "the time accessible to elementary particles is a complex rather than a real variable" should be replaced with the statement "the time accessible to elementary particles in Quantum Mechanics is a computable complex rather than a real computable variable". It is important to note that because of the limitations of instrumental setting, quantum jumps and time-mediated variables only recover computable real numbers. It is important to note that the cardinal of the collection of computable real numbers is the same as the cardinal of the collection of rational or natural numbers.

G- Quantum Chromodynamics is the quantum field theory of the strong interaction. At high energies $\ge \Lambda_{\rm QCD}$, QCD behaves asymptotically free where running coupling constants decrease by increasing energies and perturbation theory is valid to recover QCD. At low energies $< \Lambda_{\rm QCD}$, running coupling constants increase by decreasing energies where QCD behaves non-perturbatively. Confinement do happen in low energy QCD where it is expected to investigate the continuous nature of time. This suggests that there could be a fundamental relation between non-perturbation aspects of quantum systems and using complex numbers for the presentation of the nature of time. In other words, it seems that the nature of time is depended on the energy scale of the physical system. This analysis suggests that at high energies $\ge \Lambda_{\rm QCD}$, time has a discrete nature encoded by the field $\mathbb{C} \cap \mathbb{Q} \times \mathbb{Q}$. But at low energies $< \Lambda_{\rm QCD}$, time behaves continuous where we need to work on the field $\mathbb{C}$ to present time-mediated variables. Therefore the nature of time can be encoded by the duality discrete--continuous in the correspondence with the duality locality--non-locality. This theoretical investigation is another evidence to show the need for a fundamental theory which generates space-time as an emergent phenomena.

H- Here is a short list of references which provide some of mathematical and theoretical backgrounds of my comments.

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