Quantum computations without definite causal structure: TGD view

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June 20, 2019

Abstract

The notions of causal order and indefiniteness of causal order have popped up in information science. One can construct quantum computations, which cannot be carried out in fixed causal order: the simplest one is SWITCH which changes the causal order. It has been reported that the SWITCH has been realized experimentally with almost 7 sigma accuracy. In standard physics causal order is fixed and SWITCH is impossible so that the implications could be world view changing.

In TGD Zero Energy Ontology (ZEO) replaces ordinary ontology and the arrow of time is not fixed, and it is interesting to see whether superposition of different causal orders related by time inversion T for causal diamond (CD) and SWITCH could be realized in ZEO. The twistor lift of TGD leads to the proposal that CD is accompanied by a Minkowskian generalization of self-dual Kähler form $J(CD)$. Although the moduli space of CDs allows to avoid breaking of Poincare invariance, self-duality of $J(CD)$ leads to violation of T implying that different causal orders correspond to disjoint sectors of "world of classical worlds". This makes possible also superposition of different causal orders and SWITCH would map these sectors to each other.

1 Introduction

I encountered a link to a interesting popular article *"Causal Witness" Provides First Experimental Evidence Of Indefinite Causal Order* (see http://tinyurl.com/lwaurk3). The article tells about an article *Experimental verification of an indefinite causal order* by Rubio et al [B3](see http://tinyurl.com/ltamjbv). In the following are my first impressions.

In TGD Zero Energy Ontology (ZEO) replaces ordinary ontology and the arrow of time is not fixed, and it is interesting to see whether superposition of different causal orders related by time inversion T for causal diamond (CD) and SWITCH could be realized in ZEO. The twistor lift of TGD leads to the proposal that CD is accompanied by a Minkowskian generalization of self-dual Kähler form $J(CD)$. Although the moduli space of CDs allows to avoid breaking of Poincare invariance, self-duality of $J(CD)$ leads to violation of T implying that different causal orders correspond to disjoint sectors of "world of classical worlds". This makes possible also superposition of different causal orders and SWITCH would map these sectors to each other.

The abstract of the article Rubio et al might give some idea about what is involved.

Investigating the role of causal order in quantum mechanics has recently revealed that the causal relations of events may not be a priori well-defined in quantum theory. Although this has triggered a growing interest on the theoretical side, creating processes without a causal order is an experimental task. We report the first decisive demonstration of a process with an indefinite causal order. To do this, we quantify how incompatible our setup is with a definite causal order by measuring a "causal witness". This mathematical object incorporates a series of measurements that are designed to yield a certain outcome only if the process under examination is not consistent with any well-defined causal order. In our experiment, we perform a measurement in a superposition of causal orderswithout destroying the coherenceto acquire information both inside and outside of a

causally non-ordered process. Using this information, we experimentally determine a causal witness, demonstrating by almost 7 SDs that the experimentally implemented process does not have a definite causal order.

Unfortunately, I do not have prerequisites to say anything interesting about the delicacies of the experiment itself. Since causal order is fixed by that associated with space-time in standard physics, the implications of the experiment could be world view changing. The key quantum information theoretic notions are causal order, causal separability, quantum wittness, quantum process called SWITCH changing causal order, and superposition of causal orders.

1. The notion of causal order is discussed in the article "Quantum correlations with no causal order" by Oreshkov et al [B4] (see `http://tinyurl.com/l7wb5zh`). One has two events A and B. If they are causally separable, one can tell which causes which. In Minkowski space causally separable events would connected by a time-like curve. If not, one cannot speak about causal order. One can tell whether A precedes B or vice versa. For light-like distances, the situation is not so clear.

   Relaxing the standard assumption about fixed arrow of time one can at quantum level consider also a situation in which one has quantum superposition of different causal orders. One has causal non-separability.

2. The notion of causal wittness [B1] (see `http://tinyurl.com/jwzo3lq`) provides a method allowing to deduce experimentally whether the process is causally separable or not. The notion is similar to that of entanglement wittness (see `http://tinyurl.com/mwjb7um`) allowing to deduce whether the two systems are entangled. Essentially one has observable whose expectation is negative for states with indefinite causal order and positive for those with definite causal order. Causal wittness is not universal but must be constructed for each causally indefinite state separately. The construction of causal wittness expectation value of operator is far from trivial and requires deeper understanding of operator theory. The abstract definition goes as follows:

   Causal wittness represents a set of quantum operations, such as unitaries, channels, state preparations, and measurements, whose expectation value is non-negative as long as all the operations are performed in a definite causal order, i.e., as long as only causally separable resources are used. The observation of a negative expectation value is thus sufficient to conclude that the operations were not performed in a definite order.

   Causal witness can be constructed efficiently and the construction is discussed in [B2] (see `http://tinyurl.com/lxer962`).

3. SWITCH is a further basic notion. One has two events A and B, which can be connected by a time-like curve. One can tell whether A precedes B or vice versa. SWITCH is a quantum operation switching the causal order. The obvious manner to do this would permute A and B and would require "time travel" not allowed in standard physics. Obviously, SWITCH cannot be realized as operation respecting fixed causal order.

4. If superpositions of causal orders are possible, one can have a situation in which causal order is indefinite. Also this is something which does not conform the ordinary view about physics in fixed space-time but is allowed by postulates for quantum computation and SWITCH represents an example of quantum computation impossible with a fixed causal order.

Needless to say, the notions of causal order and superposition of causal orders are revolutionary ideas and the article claims that they have been experimentally verified. Standard physics framework does not allow SWITCH. Therefore there are excellent motivations to find whether these notions and the operation of SWITCH could be understood in TGD framework.

In TGD Zero Energy Ontology (ZEO) replaces ordinary ontology and the arrow of time is not fixed, and it is interesting to see whether superposition of different causal orders related by time inversion T for causal diamond (CD) and SWITCH could be realized in ZEO. The twistor lift of TGD leads to the proposal that CD is accompanied by a Minkowskian generalization of self-dual Kähler form $J(CD)$ [K5, K7]. Although the moduli space of CDs allows to avoid breaking of Poincare invariance, self-duality of $J(CD)$ leads to violation of T implying that different causal

orders correspond to disjoint sectors of "world of classical worlds". This makes possible also superposition of different causal orders and SWITCH would map these sectors to each other.

2 TGD view about causal order

2.1 ZEO and discrete symmetries for twistor lift of TGD

Some background about TGD is necessary in order to to proceed.

1. Zero Energy Ontology (ZEO) is the cornerstone of TGD and TGD inspired theory of consciousness. Zero energy states appear as two variants and correspond to different WCW spinor fields (WCW for "world of classical worlds"). I have proposed that they correspond also to WCW spinor fields localized to different sectors of WCW but this might be unnecessarily strong assumption.

   Zero energy states for given basis have been subject to a state function reduction at either boundary of CD - passive boundary. Neither the passive boundary nor the members of state pairs at it appearing in the superposition of state pairs are affected in repeated state function reductions. One has what I have called generalized Zeno effect identified as conscious entity - self.

   At the opposite boundary the states evolve: every state function reduction at active boundary is preceded by a unitary time evolution ending to a localization of the active boundary of CD, which can be also seen as a state function reduction [L2]. The temporal distance between the tips of CD increases in this process and gives rise to clock time and experienced flow of time.

   Eventually the first reduction to the opposite boundary occurs and the roles of active and passive boundary of CD are changed. One can say that time reversed zero energy state is obtained and begins to evolve. The first reduction to the opposite boundary would mean death of the conscious entity defined by the sequence of state function reductions at the same boundary and generation of time reversed re-incarnation of self.

2. Violation of T - to be discussed below - would also imply asymmetry between selves and their time reversals. For instance, the average duration for the state reduction sequences keeping boundary fixed could be different and second causal order could dominate giving rise to a dominating arrow of time. Since these reduction sequences are identified as correlates for conscious selves, the time reversed re-incarnations would live much shorter time. Biological systems might be an exception: in TGD inspired theory of consciousness sensory perception and motor action are time reversals of each other.

3. Fermionic oscillator operators associated with induced spinor fields allow to represent WCW gamma matrices as their linear combinations: Fermi statistics is geometrized. Fermionic oscillator operators define also quantum Boolean algebra in the sense that fermion numbers 1/0 correspond to the two Boolean values. One could say that quantum logic is square root of WCW Kähler geometry. This allows to interpretation the S-matrix for fermions as quantum Boolean map between quatum Boolean algebras at opposite boundaries. This is obviously important when one talks about quantum computation.

   In the approach to twistor amplitudes [K6, K7] fermions are localized at the boundaries of string world sheets defining light-like curves at the 3-D light-like orbits of partonic 2-surfaces, at which the signature of the induced metric changes from Minkowskian to Euclidian and has a vanishing determinant so that tangent space is effectively 3-D. The interpretation is in terms of strong form of holography (SH) stating that the data determining both space-time surface as preferred extremal and modes of the induced spinor field in the interior of space-time surface. SH predicts that both the bosonic and fermionic 4-D actions reduce to 2-D effective actions for string world sheets.

   The implication is that fermion states at the boundaries of CD are localized at discrete points of partonic 2-surfaces. One has of course amplitude over different locations of fermions at partonic 2-surfaces. The presence of fermionic string world sheets correlates the fermions at

different partonic 2-surfaces and serves as correlate for entanglement in fermionic degrees of freedom.

4. The twistor lift of TGD [K6, K5, K7] has led to a rather detailed understanding of discrete symmetries CP, P,T. If M^4 factor of imbedding space - or more precisely CD - is endowed with a generalized *self-dual* Kähler form $J(M^4)$ (analogs of magnetic and electric fields of same magnitude and direction), new violations of CP, P and T occurring in long scales and having no counterpart in standard model emerge. The reason is that CP, P and T do not respect the self-duality of M^4 Kähler form. The violations of Poincare invariance are avoided if one assumes moduli space for CDs containing the Lorentz boosts and translations of CD.

   The first guess is that T leaving the center point of CD invariant applied to the CD maps the 3-surfaces at the boundaries of CD to each other. The violation of T however implies that the image of the pair need not allow preferred extremal (space-time surface) connecting its members.

   One can however define the temporal mirror image of pair by mapping only the 3-surface at the passive boundary to the opposite boundary: preferred extremal property would determine the 3-surface at the passive boundary. This could imply that the sub-WCWs formed by pairs and the time reversals are disjoint and form different sectors of WCW as indeed assumed in [L2]. This realization of T allows also the possibility that the dynamics of preferred extremals is not strictly deterministic (true at least for p-adic space-time sheets).

   In absence of T violation T operation would also permute the values fermionic states partonic 2-surfaces at the boundaries of CD but if T is violated, can map only the state at the passive boundary to the opposite boundary and determine the state at original boundary from the hermitian conjugate of S-matrix in opposite time direction. The fermionic state at the opposite boundary would be superposition of states having only same total quantum numbers as the state at the passive boundary. The quantum numbers of individual fermions would not be sharp for non-trivial S-matrix if the zero energy states and their T images correspond to same sector of WCW.

   If T is not violated, zero energy states and their T-images would not correspond to the same sector of WCW. Obviously they would correspond to opposite causal orders, see below) This would force to give up the assumption that states at passive boundary are state function reduced. If T is violated globally, the zero energy states and their T-reversals would correspond to disjoint sectors of WCW, and the sectors would only correspond to different arrows of time. This option gives hopes about WCW localization the outcome of the measurement of causal order.

   The union of sub-WCWs with opposite arrow of time is a space with fixed causal order plus additional binary digit characterizing the causal order. The state function for this binary digit could fix the causal order and quantum computation generating superposition of causal orders should generate entanglement with this bit.

5. What about the situation for a union of CDs? Different CDs should be able to have their own arrow of time. For instance, there are reasons to think that in living matter one can have subsystems with non-standard arrow of time [J1]. Also phase conjugate laser ray could be also example of this. This requires that WCW spinor fields associated with a union of CDs form a tensor product. Causal order need not be same for all CDs but characterizes the sub-WCW associated with CD forming a Cartesian factor of WCW so that WCW spinors for the CDs form tensor product.

2.2 Two views about SWITCH and superposition of causal orders

One can imagine two approaches to the identification of SWITCH operation and superposition of causal orders.

2.2.1 Option I: Unitary SWITCH as time reversal

The first option corresponds to corresponds to unitary “time travel” option.

1. As already proposed, SWITCH as a unitary operation could correspond to T. Time reversal operation T applied to the 3-surfaces at the boundaries of CD would naturally change the causal order for the zero energy state. If T is violated the state and its T-image belong to separate sectors of WCW. One could also have a superposition of zero energy states related by T and having different causal orders and localizable to the two sectors of WCW.

2. Is it possible to perform SWITCH as a unitary (as a matter fact, antiunitary) operation? If T maps the disjoint sectors to each other and maps fermionic time evolutions to their time reversals, SWITCH maps the two sectors of WCW to each other.

   Can one realize SWITCH mathematically as a unitary operation between fermionic state spaces. This seems possible: the tensor product of $S \otimes S^\dagger$ on tensor product of fermionic Fock spaces would realize this map. Whether SWITCH can be realized physically is of course another question.

2.2.2 Option II: Non-unitary SWITCH as the first state function reduction to the opposite boundary of CD

Could non-unitary SWITCH be realized as the first state function reduction to the opposite boundary - death of self followed by a re-incarnation as time-reversed self? In this case SWITCH is neither unitary nor deterministic. This SWITCH corresponds to non-unitary "time travel" option in the sense that self identified as passive boundary makes a time travel to the opposite boundary of CD by re-incarnating in non-deterministic manner.

What about the superposition of self and time reversed self as a superposition of causal orders? Schrödinger cat would be more than a catchy metaphor: it would indeed be a superposition of cat and re-incarnated cat! Should one take this seriously?

If the CDs with different arrow of time correspond to different sectors of WCW, different causal orders correspond to states localized in these sectors. A superposition of causal orders would correspond to WCW spinor field having component in both these sectors. If the state function reduction to opposite boundary of CD takes place at the level of entire WCW - or more realistically, for a Cartesian factor of WCW, it must be accompanied by a localization to either sector of WCW in order to avoid paradoxes.

I have already earlier work with TGD inspired ideas related to quantum computation. For more than decade ago I developed rather speculative model topological quantum computation in TGD framework [K2, K4]. One speculation about super-effective quantum computations is inspired by the analogy of selves with quantum computations halting, when the self dies and re-incarnates as time reversed self with clock time running in opposite direction at opposite boundary of CD [K1]. This would mean using the non-unitary SWITCH realized as state function reduction in quantum computation.

This allows to imagine a series of quantum computations at opposite boundaries proceeding as a sequence of re-incarnations so that the size of CD and thus clock time would grow in opposite directions during subsequent incarnations [L1]. Although the re-incarnation as time reversed self could have long life-time, it would not be seen by an observer near the former re-incarnation and the re-re-incarnation would appear at clock-time, which need not be much later than the time of previous death. One could imagine that the time-reversed selves could have very long life-time or that the self could die and re-incarnate very many times without any-one noticing it! The large amount of time spent in time reversed mode could explain the miraculous cognitive feats of mathematicians like Ramajunan and also the magic computational abilities of idiot savants able to factorize large integers without any idea about the notion of prime.

2.3 Higher level quantum computations and ZEO

From the article of Rubio et al one ends up to an article *Quantum computations without definite causal structure* by Chiribella et al (see `http://tinyurl.com/lgjkzhx`). The article considers a rather far reaching generalization of quantum computation. Ordinary quantum computation is a time evolution of quantum states followed by a state function reduction. Since the outcome of state function reduction halting the quantum computer program is non-deterministic, the extraction of

the result involves statistical averaging over a large enough number of quantum computations to get the outcome, say prime factorization or a period of periodic function.

The notion of classical computation is generalized by Church. The computation need not be a function but can assign function to a function. One can continue this abstraction hierarchy indefinitely and it is realized formally in terms of so called Λ calculus (see `http://tinyurl.com/829fea8`). Could this hierarchy be extended to quantum computations? The quantum computation in question would be kind of super-computation assigning to quantum computation a quantum computation and entire hierarchy of quantum computations.

In TGD this kind of hierarchies emerge naturally. At space-time level there is hierarchy of space-time sheets: space-time sheet is (topologically) condensed to a larger space-time sheet and contains smaller space-time sheets condensed at it. The hierarchy of infinite primes corresponds to an infinite hierarchy of second quantizations and could relate to this hierarchy [K3] (see `http://tinyurl.com/m3tuo9q`. In each scale space-time sheets would be particles consisting of smaller particles consisting of ... Even galaxy could be seen as elementary particle in some scale characterizing the galactic space-time sheet.

The analog of quantum computational hierarchy emerges quite concretely in ZEO. The simplest zero energy states have positive and negative energy states with opposite total quantum numbers at the opposite boundaries of CD (intersection of future and past directed light-cones). One can have CDs within CDs. Furthermore, the positive/negative energy states assignable to the boundaries of CD could be also zero energy states associated with smaller CDs near the boundaries of CD. The simplest zero energy states correspond to quantum evolution representing ordinary quantum computation. Higher level zero energy stats would represent time evolution assigning to a quantum computation represented as zero energy state at the boundary of CD a second quantum computation at opposite boundary of CD.

The fermionic representation of quantum Boolean algebra makes this hierarchy quite concrete. At lowest level unitary evolution connects positive and negative energy fermionic states at opposite boundaries of CD and unitary S-matrix characterizes the computation. Higher level computations connect zero energy states assignable to sub-CDs near the boundaries of CD.

2.4 Is conscious experience without definite causal order possible?

The exciting question is what the superposition of causal orders could mean from the point of view of conscious experience. What seems obvious is that in the superposition of selves with opposite arrows of clock-time there should be no experience about the flow of time in definite direction. Dissipation is associated with the thermodynamical arrow of time. Therefore also the sensory experience about dissipation expected to have unpleasant emotional color should be absent. This brings in mind the reports of meditators about experiences of timelessness. These states are also characterized by words like “bliss” and “enlightenment”.

Why I find this aspects so interesting is due to my personal experience for about 32 years ago. I of course know that this kind of personal reminiscences in an article intended to be scientific, is like writing one’s own academic death sentence. But I also know I long ago done this so that I have nothing to lose! The priests of the materialistic church will never bother to take seriously anything that I have written so that it does not really matter! This experience - I dared to talk about enlightenment experience - changed my personal life profoundly, and led to the decision to continue work with TGD instead of doing full-day job to make money and keeping TGD as a kind of hobby. The experience also forced to realize that our normal conscious experience is only a dim shadow of what it can be and stimulated the passion to understand consciousness.

In this experience my body went to a kind of light flowing state: liquid is what comes in mind. All unpleasant sensations in body characterizing the everyday life (at least mine!) suddenly disappeared as this phase transition propagated through my body. As a physicist I characterized this as absence of dissipation, and I talked to myself about a state of whole-body consciousness.

There was also the experience about moving in space in cosmic scales and the experience about the presence of realities very different the familiar one. Somehow I saw these different worlds from above, in bird’s eye of view. I also experienced what I would call time travel and re-incarnation in some other world.

Decades later I would ask whether my sensory consciousness could have been replaced with that only about my magnetic body only. In the beginning of the experience there was indeed a

concrete feeling that my body size had increased with some factor. I even had the feeling the factor was about 137 (inverse of the fine structure constant) but this interpretation was probably forced by my attempt to associate the experience with something familiar to physicist! Although I did all the time my best to understand what I was experiencing, I did not direct my attention to my time experience, and cannot say whether I experienced the presence or absence of time or time flow.

Towards the end of the experience I was clinically unconscious for about day or so. I was however conscious. For instance, I experienced quite concretely how the arrow of time flow started to fluctuate forth and back. I somehow knew that permanent change would mean death and I was fighting to preserve the usual arrow of time. My childhood friend, who certainly did not know much about physics, told about about alternation of the arrow of time during a state that was classified by psychiatrists as an acute psychosis.

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