Still about the notion of causal indefiniteness in TGD framework

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Abstract

The light-cone of M^4 characterizes the causal structure of Minkowski space in special relativity and is the basic notion of QFTs. In curved space-time of GRT, the light-cone however depends on the metric of space-time. The intuitive view is that in quantum gravity causality becomes somehow fuzzy since there is no unique space-time anymore. What this non-uniqueness means is not clear. For instance, could it correspond to what happens in the path integral over space-times?

One cannot compare the causal structure for different space-times because the light-cones characterizing them are in different space-times. If the space-times had common coordinates, the comparison would become possible but one cannot assume this. Lucien Hardy proposes what he calls quantum Equivalence Principle. It should be possible at least locally to compare small deformations of space-time metric by finding coordinates in which the light-cone defining the causal structure co-incide.

The TGD based solution is much simpler. Space-times are identified as 4-surfaces in $H = M^4 \times CP_2$ and subset of preferred coordinate for H - Minkowski coordinates when the M^4 projection of space-time surface is 4-D - provides universal space-time coordinates and one can compare space-time surfaces and their induced causal structure. In quantum sector the second quantized free spinor fields in H can be restricted to space-time surface and define fermionic propagators and causal structure.

A closely related experimental finding is that it seems possible to construct causally indefinite photon states. In quantum switch, photon beam goes through a spin splitter to form a superposition of photons going along two paths. At the first path they go through A and then through B having some effect on the photons. At second splitter the order of A and B is changed. After that the beams are superposed and it is found that the photons in a causally indefinite state in the sense that the effects of both AB and BA are superposed. In classical physics this is impossible.

In TGD framework, the configurations AB and BA appearing in quantum switch corresponds to a space-time surface represents a branching of 3-surfaces representing photon propagation to two pieces at beam splitter and recombination back to single 3-surface making it possible for the photon wave functions interfere. Causal indefiniteness in the proposed sense does *not* mean that the direction of the causal arrow as an arrow of time is changed and in TGD framework it is not natural to speak about causal indefiniteness.

Contents

1 Introduction

The motivation for this comment came from a popular article "*Quantum mischief rewrites the laws of cause and effect*" (`https://cutt.ly/2xEP5Vd`), which tells both about the theoretical work of Lucien Hardy [B3](`https://cutt.ly/dxOdKCM`) and related experimental work, in particular about the following experimental finding [**?**] (`https://cutt.ly/GxOd4q6`.

Photon beam goes through a spin splitter to form a superposition of photons going along two paths. At the first path they go through A and then through B having some effect on the photons. At second splitter the order of A and B is changed. After that the beams are superposed and it is found that the photons in a causally indefinite state in the sense that the effects of both AB and BA are superposed. In classical physics this is impossible.

The finding is claimed to demonstrate causal indefiniteness: one does not know whether A causes B or B causes A. Classically - that is in the framework provided by fixed causal order dictated by Minkowski space - this seems to be the case.

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1. Lightcone of M^4 characterizes the causal structure of Minkowski space in special relativity and is the basic notion of QFTs. In curved space-time of GRT, the light-cone however depends on the metric of space-time. Causal structure is dynamical. The intuitive view is that in quantum gravity causality becomes somehow fuzzy since there is no unique space-time anymore. What this non-uniqueness means is not clear. For instance, could it correspond to what happens in the path integral over space-times?

2. The problem is that one cannot compare the causal structure for different space-times because the light-cones characterizing them are in different space-times. If the space-times had common coordinates, the comparison would become possible but one cannot assume this. Hardy proposes what he calls quantum Equivalence Principle (`https://cutt.ly/6xOfRQq`). It should be possible at least locally to compare small deformations of space-time metric by finding coordinates in which the light-cone defining the causal structure co-incide.

3. The TGD based solution is much simpler. Space-times are identified as 4-surfaces in $H = M^4 \times CP_2$ and subset of preferred coordinate for H - Minkowski coordinates when the M^4 projection of space-time surface is 4-D - provides universal space-time coordinates and one can compare space-time surfaces and their induced causal structure. In quantum sector the second quantized free spinor fields in H can be restricted to space-time surface and define fermionic propagators and causal structure.

   The important point is that the configurations AB and BA appearing in quantum switch corresponds to a space-time surface represents a branching of 3-surfaces representing photon propagation to two pieces at beam splitter and recombination back to single 3-surface making it possible for the photon wave functions interfere. Causal indefiniteness in the proposed sense does *not* mean that the direction of the causal arrow as an arrow of time is changed and in TGD framework it is not natural to speak about causal indefiniteness.

2 Background

2.1 What happens to causality in quantum gravity?

Lightcone of M^4 characterizes the causal structure of Minkowski space in special relativity and is the basic notion of QFTs. In curved space-time of GRT, the light-cone however depends on the metric of space-time. Causal structure is dynamical. The intuitive view is that in quantum gravity causality becomes somehow fuzzy since there is no unique space-time anymore. What this non-uniqueness means is not clear. For instance, could it correspond to what happens in the path integral over space-times?

The problem is that one cannot compare the causal structure for different space-times because the light-cones characterizing them are in different space-times. If the space-times had common coordinates, the comparison would become possible but one cannot assume this.

Lucien Hardy wanted to understand what happens for causality in quantum gravity [B3]. Hardy proposed a method to test whether events in separate space-time regions are causally related.

1. The method allows to formulate dynamical causality operationally in terms of correlations for measurements performed for regions of space-time. He also introduces the notion of an elementary region from which more complex regions giving rise to causaloids are built. Elementary region corresponds to a space-time region in which some measurement giving a definite result is performed.

   One is interested in the correlations between measurement results associated with disjoint elementary regions and in principle all measurements should reduce to a deduction of such correlations. If two disjoint regions of this kind are causally correlated, the measurement outcomes are correlated. The basic interest is in the conditional probabilities for various outcomes from the measurement of observable F_2 in region R_2 given that the measurement outcome for F_1 in R_1 is known.

   Hardy calls these structures causaloids and proposes that causaloids can be composed to form larger causaloids. No fixed causal structure is assumed and even the notion of time is in principle un-necessary in this formulation for experimental deduction of causal structure. Hardy suggests that the quantization of gravity could be performed using the notion of causaloid.

2.2 Quantum switch

Second input comes from quantum computation. Giulio Chiribella and colleagues were interested on what kind of computations are possible [B1] (`https://cutt.ly/wxEJtDF`). Classical computation can be characterized as a recursive function mapping natural numbers to natural numbers. One can build more complex functions from given functions by composition of functions. In classical computation the functions are represented as networks of Boolean gates. In quantum computation the quantum gates are used. Now the situation is more complex, since the outcome of the computation is deduced from the probabilities for various outcomes emerging as the quantum computation halts.

Chiribella and colleagues asked what kind of functions are possible. They ended up with the notion of quantum switch. Beam splitter divides the incoming photon beam to two branches. For the first branch function BA is realizes and for the second branch function AB so that one can speak of two different causal orders. After this the beams superpose. If AB and BA can be realized as causal orders, one could say that the resulting state is causally indefinite. If AB and BA are interpreted as quantum computations wihtout halting one can say that quantum switch realizes a superposition of two computations.

The quantum switch can be realized in the laboratory for the first time by Giulia Rubino et al [B2] (`https://cutt.ly/pxEH5wQ`. One can measure the polarization of the outgoing photons from the quantum switch to see whether the photons carry information about both AB and BA. This was found to be the case and the findings have been interpreted by saying that that photon experiences causal indefiniteness.

Several technological applications such as communication over noisy channels (https://cutt.ly/2xEJfVB) and quantum refrigerator based on indefinite causal order (ICO) (https://cutt.ly/cxEJcj9) have been proposed.

Hardy also proposes a Quantum Equivalence Principle [B4] stating that one can find a common reference frame for various deformations of a given space-time metric such that the light-cones of various space-time metrics co-incide in these coordinates at least locally.

3 TGD view about causal structure

In the TGD framework [L3] the basic problem of quantum gravity due to the dynamical nature of causality disappears since the imbedding space defines the pre-existing causal structure inducing the causal structure at space-time surfaces.

3.1 Induction of causal structure

The basic conceptual problem in the quantization GRT is due to inability to compare different space-times, in particular their causal structures. This problem disappears in TGD.

1. In the TGD framework the space-time of GRT is replaced with a 4-surface in $H = M^4 \times CP_2$. The topology of the space-time surface is non-trivial in all scales which leads to the notion of many-sheeted space-time allowing to reduce matter as shape to the space-time topology. Matter is not something in space-time but topological inhomogenities of space-time surface with size and shape - space-time sheets.

2. The fixed causal structure of Minkowski space M^4 defines the causal structure with induces causal structures of space-time surfaces in terms of induced metric. One can also quite concretely compare the light-cones of different space-time surfaces determined by the induced metric.

   One can also use M^4 linear coordinates as common coordinates for all space-time surfaces. If the space-time surface does not have 4-D M^4 projection, one can choose a subset of H-coordinates as space-time coordinates. By its maximal symmetries H allows very limited set of preferred coordinates sothat the problems produced by general coordinate invariance are circumvented.

   In TGD framework the surface property of space-time realizes the Quantum Equivalence Principle a at the level of imbedding space in the same way as isometries of the space-time as source of conservation laws are lifted to the level of the imbedding space.

3. In quantum TGD, also zero energy ontology (ZEO) and causal diamond (CD) are basic notions. CD represents the perceptive field of a conscious entity. The notion of CD resembles the notion of causaloid. One can assign a CD to any quantum system, even elementary particle. CDs form an analog of an atlas consisting of charts and there is a fractal hierarchy with CDs inside CDs, and also overlapping CDs.

4. Zero energy states inside CDs represent particle states as extended objects rather than points. Zero energy states associated with CD correspond to superpositions of space-time surfaces identifiable as preferred extremals of an action principle deriving from the twistor lift of TGD. Minimal surfaces, which are also extermals of so called Kähler action, are in question - minimal surface property geometrizes the notion of massless field and extrelality also for Kähler poses extremely powerful additional conditions guaranteeing Bohr orbit like character of the space-time surface needed to realize general coordinate invariance.

   The important point is that the configurations AB and BA appearing in quantum switch corresponds to a space-time surface represents a branching of 3-surfaces representing photon propagation to two pieces at beam splitter and recombination back to single 3-surface making it possible for the photon wave functions interfere. Causal indefiniteness in the proposed sense does *not* mean that the direction of the causal arrow as an arrow of time is changed and in TGD framework it is not natural to speak about causal indefiniteness.

5. Concerning the understanding of the causality at quantum level in TGD Universe, induction is the key notion. All geometric structures are induced from those of H. This applies to metric, spinor connection, spinor structure, and twistor structure.

   In particular, second quantized spinor field of H is a superposition of modes of the massless Dirac operator of H, which can be solved explicitly and one can calculate Dirac propagator [L4]. The induction of the second quantized spinor field means a restriction to space-time surface and propagators at space-time surface are simply propagators in H. There are no problems with causality since it is induced from H to space-time surfaces.

3.2 Also a genuine change of the arrow of time is possible in ZEO

TGD however predicts a different kind of causal anomaly: the arrow of time can change and induce the change of the thermo-dynamical arrow of time [L2].

1. TGD predicts that two kinds of fermionic vacua corresponding intuitively to Dirac seas for which either all negative energy states or positive energy states are filled. They are present also in QFTs but one selects only the second one.

   The fermionic creation/annuhilation operators for the first vacuum act like annihilation/creation operators for the second vacuum. In ZEO these two fermionic vacua are associated with the opposite boundaries of CD.

2. Zero energy states as pairs of states assignable to the boundaries of CD. By conservation laws one can say that the total quantum numbers of CD vanish so that the total quantum numbers for the boundaries of CD are opposite.

3. In ZEO [L2, L5] there are two kinds of state function reductions (SFRs): "big" SFRs (BSFRs) as counterparts of ordinary SFRs and "small" SFRs (SSFRs) as counterparts of "weak" measurements as quantum analogs of classical measurements. In BSFRs the arrow of time changes and therefore cause and effect change their roles.

4. Either boundary of the CD is the passive boundary. Neither the passive boundary nor states at it change during the sequences of SSFRs. One can say that the Zeno effect is realized at the passive boundary.Active boundary recedes from the passive boundary in a sequence of scalings of CD followed by SSFRs preceded by unitary time evolutions. Therefore also the states at the active boundary change.

5. In BSFR the active boundary becomes passive and vice versa. The time reversal occurs for dark matter with $h_{eff} = nh_0$ residing at magnetic bodies, and since MB controls the dynamics of ordinary matter, BSFRs for MB induce effective change of the arrow of time for the ordinary matter in scales much longer than it would occur normally in BSFRs in the scale of microcosmos.

6. The change of the thermo-dynamical arrow of time changes in BSFR implies thermo-dynamical anomalies such as generation of gradients observed in systems with a reversed arrow of time [L1]. For instance, the time reversed system can effectively extract thermal energy from the environment. Actually this would be dissipation with a reversed arrow of time. Time reversal also makes self-organized quantum criticality (QSOC) possible [L6], and homeostasis could be seen as the biological manifestation of QSOC.

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