Topological order and Quantum TGD

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Abstract

Topological order is a rather advanced concept which has been established in condensed matter physics. There are several motivations for the notion of topological order in TGD.

1. TGD can be seen as almost topological QFT. 3-D surfaces are by holography equivalent with 4-D space-time surfaces and by strong form of holography equivalent with string world sheets and partonic 2-surfaces. What make this duality possible is super-symplectic symmetry realizing strong form of holography and quantum criticality realized in terms of hierarchy of Planck constants characterizing hierarchy of phases of ordinary matter identified as dark matter. This hierarchy is accompanied by a fractal hierarchy of sub-algebras of supersymplectic algebra isomorphic to the entire algebra: Wheeler would talk about symmetry breaking without symmetry breaking.

2. $h_{eff} = n \times h$ hierarchy corresponds to n-fold singular covering of space-time surface for which the sheets of the covering co-incide at the boundaries of the causal diamond (CD), and the n sheets together with super-conformal invariance give rise n additional discrete topological degreees of freedom - one has particles in space with n points. Kähler action for preferred extremals reduces to Abelian Chern-Simons terms characterizing topological QFT. Furthermore, the simplest example of topological

order - point like particles, which can be connected by links - translates immediately to the collections of partonic 2-surfaces and strings connecting them.

3. There is also braiding of fermion lines/magnetic flux tubes and Yangian product and co-product defining fundamental vertics, quantum groups associated with finite measurement resolution and described in terms of inclusions of hyper-finite factors.

In this article topological order and its category theoretical description are considered from TGD point of view - category theoretical notions are indeed very natural in TGD framework. The basic finding is that the concepts developed in condensed matter physics (topological order, rough description of states as tangles (graphs imbedded in 3-D space), ground state degeneracy, surface states protected by symmetry or topology) fit very nicely to TGD framework and has interpretation in terms of the new space-time concept. This promises applications also in the conventional areas of condensed matter physics such as more precise description of solid, liquid, and gas phases.

1 Introduction

There was a very interesting link in Thinking allowed original to an article telling about the category theoretical description of topological order [B2] (`http://arxiv.org/abs/1507.04673`). The description of non-Abelian Quantum Hall in terms of patters of zeros of multi-electron wave function and using so called Z_n current algebra states is considered in [B1].

Topological order means emergence of discrete degrees of freedom implying ground state degeneracy and long range correlations, even long range entanglement. Topological order appears in 2+1-D systems. Braiding and braid statistics characterized by R-matrix are central elements. There is also a connection with integrable 2-D quantum field theories. The generalization of R-matrix defines 2-particle S-matrix defining the building brick of N-particle S-matrix in 2-D integrable quantum field theories: the basic interaction is passing-by inducing a phase lag. For braids the exchange is a continuous homotopy and braiding dynamics could make possible topological quantum computation [K5].

One cannot avoid the feeling that topological order is exactly the mathematical tool needed in quantum TGD. On basis of what I have learned recently [L1, ?] (see this and this), condensed matter physicists might be discovering many-sheeted space-time and exotic effects predicted by quantum TGD without realizing what they are doing! I have believed hitherto that this would be something for elementary particle physicists but they are sunken into the multiverse muds of M-theory landscape.

There are several reasons to believe that the notion of topological order in TGD could be very useful in more concrete formulation of quantum TGD.

1. TGD can be seen as almost topological QFT. 3-D surfaces are by holography equivalent with 4-D space-time surfaces and by strong form of holography equivalent with string world sheets and partonic 2-surfaces. What make this duality possible is super-symplectic symmetry [K4, K3] realizing strong form of holography and quantum criticality realized in terms of hierarchy of Planck

constants characterizing hierarchy of phases of ordinary matter identified as dark matter. This hierarchy is accompanied by a fractal hierarchy of sub-algebras of supersymplectic algebra isomorphic to the entire algebra [K14]: Wheeler would talk about symmetry breaking without symmetry breaking.

2. $h_{eff} = n \times h$ hierarchy corresponds to n-fold singular covering of space-time surface for which the sheets of the covering co-incide at the boundaries of the causal diamond (CD), and the n sheets together with superconformal invariance give rise n additional discrete topological degreees of freedom - one has particles in space with n points. Kähler action for preferred extremals reduces to Abelian Chern-Simons terms characterizing topological QFT. Furthermore, the simplest example of topological order - point like particles, which can be connected by links - translates immediately to the collections of partonic 2-surfaces and strings connecting them.

3. There is also braiding of fermion lines/magnetic flux tubes and Yangian product and co-product defining fundamental vertices, quantum groups associated with finite measurement resolution and described in terms of inclusions of hyper-finite factors [K11] .

Number theoretic vision [K14] - in particular adelic physics - is an additional building brick in TGD. It would be nice to see what comes out from the combination of topological order with the hierarchy of algebraic extensions of rationals and associated extensions of p-adic number fields by extending the physics to adelic physics. The existence of this extension must pose powerful constraints on physics.

In this article topological order and its category theoretical description are considered from TGD point of view - category theoretical notions are indeed very natural in TGD framework. The basic finding is that the concepts developed in condensed matter physics (topological order, rough description of states as tangles (graphs imbedded in 3-D space), ground state degeneracy, surface states protected by symmetry or topology) fit very nicely to TGD framework and has interpretation in terms of the new space-time concept. This promises applications also in the conventional areas of condensed matter physics such as more precise description of solid, liquid, and gas phases.

The following considerations can be blamed to be "just philosophy" since I am not a condensed matter physics and do not try to pretend being computational virtuoso. What I dare argue that TGD allows much more wider perpective than is possible inside the boundaries posed by specialization. My hope is that the reader would realize that TGD provides fascinating challenges and inspiration for theoretical physicist - even those working in condensed matter physics.

2 What does topological order mean?

Topological order is something not describable by local order parameters allowing to characterize different phases by their different symmetries using Landau theory. Fractional Quantum Hall effective is simplest example of this: all phases have the same symmetries. One signature is the existence of several degenerate ground states.

As already noticed, in the fractal Universe of TGD one has a hierarchy of quantum criticalities with levels labelled by $h_{eff} = n \times h$ giving rise to "symmetry breaking without symmetry breaking" in terms of an inclusion hierarchy of isomorphic mutually isomorphic subalgebras of super-symplectic algebra. Could this hierarchy lurk behind the existence of phases with identical symmetries? This hierarchy makes sense also for the ordinary conformal invariance, which is much smaller symmetry than super-symplectic one and replaces AdS/CFT duality with more physical looking duality defined by strong form of holography.

For some reason colleagues have not noticed the possibility of this kind of conformal symmetry breaking. This is not the only rather trivial fact that has escaped the attention of hasty colleagues during last decades. The completely unique role of 4-D space-time, the twistorial uniqueness of $M^4 \times CP_2$ [K10], and the fact that CP_2 codes for standard model symmetries, have also remained un-noticed.

The article *Detecting topological order in a ground state wave function* by Levin and Wen gives an idea about what topological order is. The simplest situation in which topological order is encountered, is when one has a set of objects such that each pair can be connected by link. The pair can be characterized by "spin" telling whether its members are connected or not. In condensed matter physics one could have lattice like structure with link between given neighboring points or not. This is very special situation. In principle all possible configurations involving links between objects are possible. One could of course pose additional conditions such as as imbedding of the vertices as lattice, restriction of the links to nearest neighbour links, allowance of only single link between members of pair, and some maximum number of links emanating from given object.

What does topological order mean in quantum theory?

1. In topological quantum computation each braid topology defines unitary S-matrix and one has only single braid topology. Topology is still classical and fixed although the dynamics in this fixed topology is quantal.

2. There is however no deep reason to assume localization into a single topology. This mixing could occur already in particle physics. The TGD based explanation of family replication phenomenon [K2] assumes that quantum superpositions of the topologies of partonic 2-surfaces characterized by genus and that CKM matrix reflects different topological mixings for U and D type quarks [K8]. Ground state wave function would be quantum superposition of graph topologies. Even more: for given graph one would have also a superposition of different imbeddings to 3-space as tangles characterized by knotting and linking.

One can formally describe the topology in terms of "topological spins".

1. For a quantum graph each topological configuration of the system is quantum superposition of graphs with some pairs of vertices connected by link or not. What is fixed are the vertices. One can assign to each pair "spin" -1/1 telling whether the connecting link is present or not. One could assume that each vertex is connected to at least one vertex to exclude lonely vertices. This gives a large number of graphs and ground state is quantum superposition of these

graphs. This brings in the long range quantum entanglement between pairs. Some kind of reference configuration could be a graph in which all objects are connected to every other object once.

2. The imbedding of graph to 3-D space gives tangle. Tangle consists of several groups of vertices from which connecting links emerge. By fractality one can also tangles within tangles. Tangle can be characterized by its projection to a suitably chosen plane. In the projection two tangle strands cross and there are two different crossings depending which strand is above which. This defines second spin like variable characterizing tangles.

3. In TGD space-time also 2-braiding is possible. 2-braid can be thought of as an evolution of ordinary knot giving rise to 2-D surface in 4-D space-time. One an have un-knotting or its reversal of knots by a violent manner: the braid strands go simply through each other. Knot invariants are actually constructed by performing this violent un-knotting step by step. A spin like variable telling whether this occurs for a pair of braid strands appearing in 2-knot is needed.

The article considers a lattice in which links are possible between neighboring lattices points. The ground state is a superposition over all link paths as a state with long range entanglement: the product of spins equals to 1 for all closed loops crossing a given curve since the loops intersect the curve always even number of times (this is where topology shows itself!) Could this kind quantum superposition be the first principle approach when one wants to describe many particle system? Liquid, gas, and solid phases would be of course hugely simplified descriptions in this picture. The basic unpleasant question is obvious: can long links be really thermally stable in standard physics?

3 Topological order and category theory

The article summarizes the proposal to describe topological order in terms of category theory. In reductionistic approach one decomposes the object to smaller and smaller pieces. In particle physics the actions of symmetries on object characterize the object in terms of quantum numbers. In category theoretical approach one describes the system in terms of its relations with other systems. Relations corresponds to morphisms mathematically and are deduced by studying the interactions with other systems. How particle interacts with the other particles defines what particle is.

At the level of topology the braiding of object with other objects provides this kind of basic morphism. Fusion or stacking with other objects defines second morphism. The integer valued coefficients of fusion telling which quantum objects appear in the stacking of the object with another object provide information about objects via its relations. Fusion has splitting as its reversal. Algebraically product and co-product correspond to these operations and I have proposed that zero energy states as transition amplitudes represents sequences algebraic operations - product and co-product identified essentially as 3-particle vertices - in Yangian algebra closely related to category theoretical approach [K10]. Particle vertices would represent additional morphisms besides braiding.

Category theoretical approach can be made quantitative in terms of integers N_k^{ij} telling the multiplicity for representation k in the fusion of representations i and j and fractionals spins s_i characterizing the braid statistics. The category in question must involve also the counterpart of tensor product since in physics one must engineer more complex systems from simpler ones. One speaks of tensor category.

One can define stacking of topological orders serving as the counterpart for tensor product and making topological orders a monoid. Stacking is not ordinary tensor product since there is some inherent entanglement always present. I dare to guess that a special case of Connes tensor product is in question [K11]. This inherent entanglement eliminates a lot of states from the ordinary tensor product. Stacking is interpreted in condensed matter context as formation of multilayers.

If stacking by a given topological order leaves other topological orders as such, the topological order is trivial. A non-trivial topological order can have an inverse: this is equivalent with having no topological excitations. The inverse of the topological order is obtained by time reversal operation acting as symmetry. Non-invertible topological orders correspond to non-Abelian braid statistics.

The basic result of article does not say at the first glance too much to a non-specialist. *Up to an invertible topological order 2+1-D fermionic/bosonic topological orders with/without symmetry are classified by modular braided fusion categories (BFC) over symmetric BFC, where symmetric BFC describes product state with/without symmetry.*

I understand that symmetric BFC corresponds to invertible topological orders acting via the stacking and not affecting the topological order: this is like multiplying vector with scalar in projective space.

4 Category theoretical description of topological order TGD

Much of the philosophy and mathematical building bricks of this vision are shared by quantum TGD. The notions of topological order, stacking, and gapless states represent however something new and are highly interesting concerning the more detailed formulation of quantum TGD. This kind of approach is not all that is needed in TGD but could give the tools needed to build the roughest topological characterization of spinor fields in the "world of classical worlds" (WCW) at many-particle level.

4.1 Topological order in TGD

In quantum TGD combinatorial description in terms of graphs would give the roughest topological description of the ground state in terms of partonic 2-surfaces (vertices) and fermionic strings or magnetic flux tubes (links) connecting them. It must be made clear, that topological order in TGD sense means radical deviation from the standard model thinking in which space-time is fixed background. This goes also beyond the descriptive powers of the long length scale limit of string models assuming that space-time serves as arena of dynamics.

There are two basic topological elements besides many-sheetedness: the graph structure characterized by telling which partonic 2-surfaces are connected by strings/flux tubes and the tangle structure present because there exists infinite number of topologically non-equivalent imbeddings of the graph to 3-D space. 4-D space-time thus allows richest possible topological order besides gigantic super-symplectic symmetries.

1. The strings/flux tubes could connect different partonic surfaces and also return back to the same partonic 2-surface but at different point carrying fermion number. Strings and flux tubes get knotted and linked in 2+1 dimensional situation. The outcome is tangle. If there are only two partonic 2-surface no self-entangling one has braid.

2. For partonic 2-surfaces carrying several fermions also self-tangles are possible and one can have quantum superposition of different self-tangles. Flux tubes of dipole magnetic field serve as an illustration.

3. Also the many-sheeted character of space-time gives additional topological degree of freedom in TGD framework. In TGD Universe even elementary particles are structures with at least two space-time sheets since they consist of a pair of wormhole contacts connecting two space-time sheets and wormhole throats at both sheets are connected by flux tubes carrying monopole flux and fermionic strings. For large values of h_{eff} the size of these structure is scaled up so that one could electrons with size scale of cell! As discussed below, many-sheetedness could correspond to what is called stacking of topological orders.

Topological order defined by links is robust and not affected by thermal fluctuations unless the links are thermally unstable. Thermal stability at high temperatures can be argued to be an ad hoc assumption in standard physics. In TGD framework the thermal stability of long links would be due to the hierarchy of Planck constants $h_{eff} = n \times h$. This could make possible long range quantum entanglement between distant topological spins possible in high temperatures.

What about applications? Can one apply the notion of topological order only to low exotic condensed matter systems at low temperature? TGD suggests that applications are possible even at room temperatures.

1. The distinction between liquids and gases is not really well-understood in text book statistical physics missing strings as fundamental objects so that one has only the point particles - partonic 2-surfaces in TGD - and potential function modelling the interactions between them. Topological order replacing potential function with strings/flux tubes should allow an improved understanding the distinction between fluids and gases.

2. The clusters of water molecules are problematic in the standard model description of water, and are crucial in the physics of living matter (consider only the fourth phase of water discovered by Pollack). The existence of strings connecting partonic 2-surfaces would make the clusters of liquid molecules in TGD framework. There is also a connection with $h_{eff} = n \times h$ hypothesis

made rigorous by the hierarchy of quantum criticalities explaining dark matter. The longer the flux tubes defining the link needed for clustering are, the larger the value of h_{eff} must be, and the value of h_{eff} characterizes the length scale in which quantum coherence is present.

3. Reductionist finds it convenient to assume that nuclear physics is totally isolated from the condensed matter physics. There are anomalies challenging this hypothesis. For instance, X rays from Sun with energies in the energy scale of transition energies of heavier ions are found to affect the nuclear decay rates so that they vary periodically with period of year [K7]. Could condensed matter transitions do the same trick?

   The claims about cold fusion represents second example [K7] Most main streamers refuse to even consider cold fusion as a possibly real phenomenon. The flux tubes carrying dark quarks with large h_{eff} would bind nucleons to form nuclei and they could be so long as to make possible interactions with condensed matter. They could explain several other anomalies such as the anomalous value of proton radius.

4.2 Stacking, time reversal, and gapless states in TGD framework?

Stacking can be seen as a constrained tensor product. It could have several interpretations in TGD framework.

1. Stacking might correspond to a formation of quantum states assignable to many-sheeted structures formed from single sheeted structures? Stacking would occur already as one forms elementary particles as double-sheeted structures. Could it be involved with the formation of n-sheeted coverings associated with $h_{eff}/h = n$ and quantum criticality?

2. Topological condensation of a smaller space-time sheet to a larger space-time sheet might have interpretation in terms of stacking? Topologically condensed space-time sheet cannot be represented as a tensor factor in TGD framework. Can the situation be described as a pair of included and including factors with included factor defining measurement resolution for the including factor? Connes tensor product is indeed associated with the inclusion?

3. Many-sheeted space-time suggests the rather exotic looking possibility that two disjoint space-time sheets can have topologically condensed smaller space-time sheets (like liquid drops of the wall) connected to each other by thin flux tubes not visible in the scale of bigger space-time sheets - entanglement would be a resolution dependent notion. In the scale of the bigger space-time sheet one would have ordinary tensor product without entanglement. In the scale of smaller space-time sheets one would have entanglement: subsystems of un-entangled systems would entangle. This has a direct application in TGD inspired theory of consciousness: sub-selves (mental images) of self can fuse to stereo mental image shared by the selves although selves do not entangle and remained separate conscious entities [K9].

Could this be described in the formalism based on categories? Is the notion of resolution inherent to this description? The inclusions of hyper-finite factors can be interpreted in terms of finite measurement resolution, and the description of inclusions indeed involves quantum groups as also topological order. The larger space-time sheet seen in the resolution defined by topological condensed space-time sheets would be characterized by quantum space with fractional quantum dimension resulting by modding out the degrees of freedom of topologically condensed space-time sheets.

4. One can imagine a further interpretation for stacking. Negentropic entanglement between states associated with separated space-time sheets could also give rise to a restricted tensor product [K6]. Negentropic entanglement (NE) can be algebraic such that the coefficients belong to the algebraic extension of rationals characterizing the adele but entanglement probabilities are outside this extension, which encourages the hypothesis that diagonalization is not possible and this kind of NE is stable. NE can also correspond to a projector in which case state function reduction need not lead to an eigen ray since the whole sub-space is eigenspace of density matrix.

Time reversal defines inverse topological order provided one can regard it as a symmetry. For instance, time reversal symmetry protects topological insulator. More generally, one can have symmetry protected topological order (SPT), which is actually trivial topological order but without long range entanglement. Symmetry protected states do not lead to emergent fractional charge, fractional statistic, nor emergent gauge gauge theory unlike topological order. In TGD framework the emergent gauge symmetry could be identified as a symmetry associated with the action of included hyperfinite factor, which indeed causes no measurable effects in the resolution used.

Here an interesting delicacy appears. Is its particle physicist's time reversal, which is slightly broken symmetry? Or is it time reversal in the sense of TGD inspired theory of quantum measurement and consciousness bringing in the arrow of time (or thermodynamics)? Time reversal in the latter sense cannot be interpreted as a symmetry. For instance, time reversal in the latter sense involves state function reduction at opposite boundary of CD, which is dynamical and non-deterministic process leading to death of self and its re-incarnation as time reversed self. Note that time reversal is not allowed for non-Abelian braid statistics and although Kähler action is abelian the vierbein group of CP_2 is non-Abelian and can give rise to non-Abelian braiding by electroweak gauge group.

Gapless boundary excitations implying ground state degeneracy are also an important part of picture.

1. In the case of topological order they are robust against all local perturbations and protected by topology. Systems described by topological QFTs provide a basic example about non-trivial topological order. In the case of SPTs one has only robustness against local perturbations that do not break symmetries.

2. Super-symplectic algebra provides a concretization of the situation in TGD context. The sub-algebra of supersymplectic algebra with conformal weights,

which are $h_{eff}/h = n$-ples of those for entire algebra act as gauge transformations and are thus perturbations, which do not change the state: one could say that there is symmetry protection. This differs from topological protection since not all deformations of 3-surfaces at the ends of space-time at boundaries of CD act like gauge symmetries. Indeed, the remaining generators of super-symplectic algebra act as genuine dynamical symmetries and if the generators with conformal weights $0 \leq k \leq n-1$ create physical states one indeed has finite degeneracy of states (this if the conformal weights of the super-symplectic algebra are integers). This gives just the n-fold degeneracy corresponding to singular n-sheeted covering property of space-time surface. Of course, the is a huge difference: usually one deals with finite-D or even discrete groups whereas super-symplectic group is really huge.

To test TGD one must be able to see the physics of single space-time sheet. The difficulty is that usually this physics is masked experimentally: usually we see only the superposition of effects from several sheets. It is also masked theoretically in the approximation based on the space-time of General Relativity and standard model since it is obtained by replacing many-sheeted space-time by a slightly curved region of Minkowski space involving replacement of induced gauge potentials resp. gravitational fields of space-time sheets with their sum defining the gauge potentials of standard model resp. gravitational field of GRT, replacing partonic 2-surfaces by point like particles, and describing fermionic strings in terms of interaction potentials. Condensed matter physicists might be already occasionally seeing the physics of single space-time sheet.

4.3 Category theory and TGD

Category theoretical thinking is part of TGD [K1].

1. In reductionistic approach particles are fundamental building bricks. The idea about an isolated particle must be given up in TGD. The strings connecting partonic 2-surfaces are present from beginning rather than only the partonic 2-surfaces, which are the counterparts of particles in the reductionistic approach. Note that in string models one has strings but no partonic two-surfaces so that one still remains in the framework of reductionism!

   This has highly non-trivial implications for the understanding of the formation of gravitational bound states and from TGD point of view the failure of superstring models in long length scales is trivial to understand: superstring description of gravitational interactions makes sense only in Planck length scale: the rest is - not history but - wishful thinking eventually leading to landscape and multiverse [K13](`http://matpitka.blogspot.fi/2015/03/is-formation-of-gravitational-bound.html`).

2. Zero Energy Ontology (ZEO) [K12, K6] is very category theoretical approach. One gives up the notion of positive energy state in ZEO. Positive energy states are replaced with zero energy states, which are pairs of positive and negative energy states at opposite boundaries of causal diamond (CD) and have opposite quantum numbers. Zero energy state is analogous to event in standard

ontology consisting of initial and final state. Object is replaced with a relation between objects, one might say.

Zero energy states are described by M-matrices (M-matrix is expressible as products of square root of density matrix and unitary S-matrix). Dynamics is coded by unitary U-matrix expressible in terms of M-matrices so that states code the dynamics in their representation. ZEO shows its power in TGD inspired theory of consciousness and allows to replace observer as an outsider of the physical world with the notion of self, a conscious entity describable in terms of quantum physics.

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