TGD based model for graphene superconductivity

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Abstract

Cao et al have found that a system consisting of two parallel graphene layers rotated with respect to each other by a critical twist angle of 1.1 degrees becomes a Mott insulator behaving like single unit rather than two weakly interacting conductors. The application of electric field transforms the system to a super-conductor. This finding is believed to be highly significant concerning the understanding of high T_c super-conductivity. The finding motivates the development of a model of Mott insulators based on TGD based views about valence bond inspired by the identification of dark matter as $h_{eff}/h = n$ phases of ordinary matter emerging naturally in adelic physics. This allows to develop in more detail also the TGD based model of high T_c super-conductivity.

1 Introduction

A highly interesting new effect associated with graphene is discussed in Phys.Org article (see http://tinyurl.com/ydyqgk56). The original research articles by Cao et al are published in Nature [D1, D2]. There is also a popular article In Nature (see http://tinyurl.com/ya5jzadc). What is found that a bilayer formed by parallel graphene sheets becomes superconducting for critical values of twist angle θ. The largest critical value of θ is $\theta = 1.1$ degrees.

1.1 Basic observations

Consider first basic facts. The surprising discovery was that graphene becomes unconventional superconductor at temperature 1.7 K. It was already earlier discovered that the coupling of graphene to a superconductor can make also graphene superconducting.

1. The system studied consists of two graphene (see http://tinyurl.com/8os5eas) layers twisted by angle θ with respect to each other (rotation of the second sheet by angle θ around the axis normal to sheets). For a generic value of θ the graphene layers behave as separate conductors. For certain critical twist angles below 1.1 degrees the two-layered system however behaves like single unit and Mott insulator (see http://tinyurl.com/ybqblvc7): this is due to the increase of the conduction band gap. In an applied electric field the system becomes a super conductor. The electric field provides the energy needed to kick the current carries to the conduction band, which for Mott insulators has higher energy than for the corresponding conductor: at the top of the band Cooper pairs are formed as in the case of ordinary superconductors.

2. A kind of Moire effect (see http://tinyurl.com/qchunes) is involved. The twist creates a superlattice with larger unit cell and the electrons associated with periodically occurring C-atom pairs above each other give rise to a narrow band where the superconducting electrons are. Electric field would kick the electrons to this band.

3. There are intriguing analogies with high T_c superconductivity. Electron density as function of temperature has a pattern similar to that for cuprates. Superconductivity occurs at electron density, which is 10^{-4} times that for conventional superconductors at the same temperature. The pairing of electrons cannot be due to phonon exchange since the density is so low. Unidentified strong interaction between electrons is believed to be the reason.

1.2 TGD based view very briefly

The finding of Cao et al is believed to be highly significant concerning the understanding of high T_c super-conductivity and motivates the development of a model of Mott insulators based on TGD based views about valence bond inspired by the identification of dark matter as $h_{eff}/h = n$ phases of ordinary matter emerging naturally in adelic physics [K11] [L4]. Also a more detailed version about the model of high T_c superconductivity in TGD Universe developed in [K1, K2, K7, K8] emerges.

The model starts from a model of elementary particles applied to electron.

1. At space-time level elementary particles are identified as two-sheeted structures involving a pair of wormhole contacts connecting the space-time sheets and magnetic flux tubes connecting the wormhole throats at the two sheets. For the second sheet flux tubes are loop-like and define the magnetic body of the particle. These flux loops are associated with valence bonds and the value of $h_{eff}/h = n$ can be large for them implying that the loops become long. In ohmic conductivity the reconnection of the valence loops would be the fundamental mechanism allowing to transfer conduction electrons between neighboring lattice sites.

2. An essential role is played by TGD based model for valence bond predicting that the value of n increases along the row of the Periodic Table. For group 4 transition metals n for valence bond with O is largest for Ni (NiO is Mott insulator) and for Cu (copper oxides are high T_c superconductors) so that they are predicted to be excellent candidates for Mott insulators and even unconventional superconductors.

3. TGD space-time time is many-sheeted and flux tubes form a hierarchy. In high T_c superconductivity also anti-ferromagnetic (AFM) flux loops with a shape of flattened and elongated rectangle would be present. The reconnection of valence flux loops with AFM flux loops would allow the transfer of the precursors of Cooper pairs - appearing already for Mott insulators but not yet giving rise to super-conductivity - to the AFM flux loops. In the phase transition leading to high T_c superconductivity in macroscopic scales the AFM flux loops would reconnect to longer flux loops making possible macroscopic supra currents.

2 Mott insulators, transition metals, antiferromagnets, and high T_c superconductors in TGD framework

In 1937 Jan Hendrik de Boer and Evert Johannes Willem Verwey pointed out that a variety of transition metal oxides are insulators although they should be conductors since they have odd number of electrons per lattice cells. Nevill Mott and Rudolf Peierls predicted that the effect can be explained by taking into account the interaction between electrons neglected in the band theory of solids. These materials became known as Mott insulators (see `http://tinyurl.com/ybqblvc7`).

1. 1949 Mott proposed a model for NiO as insulator (Ni is transition metal). The conduction was based on the process $(Ni^{2+}O^{2-})^2 \to Ni^{3+}O^{2-} + Ni^{1+}O^{2-}$. In this process electron is transferred between the neighboring sites. For critical values of parameters NiO however becomes insulator.

   The formation of energy gap preventing conduction can be understood as competition between Coulomb potential U between 3d electrons at the same site and the transfer integral t of 3d electrons between neighboring sites characterizing the transfer of electron between neighboring sites. The total energy bap is $U - 2zt$, where z is the total number of nearest-neighbor atoms. As U is increased by varying parameters a transition to insulator takes place when the energy gap becomes too large.

   t is essentially the matrix element of atomic potential ΔU due to the neighboring atoms taken between two electronic orbitals associated with neighboring atoms. Usually this matrix element is small.

2. It is believed that ordinary quantum mechanics can explain the needed large magnitude of t. The calculations are however not first principle calculations and involve experimental input

from chemical bond energy data. Therefore one can ask whether some new physics possible related to the notion of valence bond might be needed.

In TGD framework one indeed ends up to a model of valence bonds involving non-standard value of $h_{eff}/n = n$ for valence bonds. This could lead to a delocalization of electron wave functions and generate strong interaction between valence electrons of neighboring atoms. This mechanism might apply to all strongly interacting many-electron systems (such as that appearing in QHE and FQHE [K6]) so that the physics of dark matter would make itself visible in condensed matter physics thought to be thoroughly understood at the level of basic principles.

Remark: The original motivation for the hierarchy of Planck constants was the idea that Nature loves theoreticians [K4, K10]. The phase transition increasing the value of Planck constant reduces the large value oof gauge coupling constant $\alpha = g^2/4\pi\hbar$ making perturbation theory impoessible by factor $1/n$ and makes perturbation theory possible.

The TGD based picture about Mott insulators relies on $h_{eff}/h = n$ hierarchy giving rise to dark matter as phases of ordinary matter. In particular, one ends up with a model for valence bonds with valence electrons having value of n larger than for atoms. This in turn leads to a model of high T_c superconductivity generalizing to a model of Mott insulators. Also graphene superconductivity would rely on these mechanisms.

2.1 Dark matter as $h_{eff}/h = n$ phases

It is good to explain first the development of the ideas related to $h_{eff}/h = n$ hierarchy.

1. I ended up to the discovery of dark matter hierarchy and eventually to adelic physics [L4], where $h_{eff}/h = n$ has number theoretic interpretation along several roads starting from anomalous findings.

   One of these roads began from the claim about the existence of strange form of matter by David Hudson [H1]. Hudson associated with these strange materials several names: White Gold, monoatomic elements, and ORMEs (orbitally re-arranged metallic elements). Any colleague without suicidical tendencies would of course refuse to touch anything like White Gold even with a 10 meter long pole but I had nothing to lose anymore. The basic feature is that these elements would form metal like strongly correlates structure although the atoms are separate so that their is no lattice in the usual sense.

   My question was how to explain these elements if they are actually real [K1, K3]. If all valence electrons of this kind of element are dark these element have effectively full electron shells as far as ordinary electrons are considered and behave like noble gases with charge in short scales and do not form molecules. Therefore "monoatomic element" is justified. Of course, only the electrons in the outermost shell could be dark and in this case the element would behave chemically and also look like an atom with smaller atomic number Z. So called Rydberg atoms for which valence electrons are believed to reside at very large orbitals could be actually dark atoms in the proposed sense.

   Obviously also ORME is an appropriate term since some valence electrons have re-arranged orbitally. White Gold would be Gold but with dark valence electron. The electron configuration of Gold is $[Xe]4f^{14}5d^{10}6s^1$. There is single unpaired electron with principal quantum number $m = 6$ and this would be dark for White Gold and chemically like Platinum (Pt), which indeed has white color.

   Remark:: The precious metals involved are also transition metals near the end point of the group along the row of the periodic table as are also Mott insulators.

   The ability of ORMES consisting of single isolated atoms to behave like condensed matter system would be due to the presence of long magnetic flux tubes assignable to valence electrons with large n and connecting the atoms of ORMUS together. For ordinary valence bonds the flux tubes are short and one obtains ordinary metal lattice.

2. Developments at quantitative level began with the TGD based explanation [L3] (see `http://tinyurl.com/y8pqcc8s`) for the finding that in heating of a system involving transition

metal unpaired valence electrons mysteriously disappear. The increase of $h_{eff} = n \times h$ for valence electrons in transition metals from their normal value would explain how they become dark matter in TGD sense. Since the binding energy associated with the bond increases with n, energy is required to kick electrons to the dark valence band and heating provides it. In TGD inspired quantum biology, metabolic energy increases the value of n for valence bonds and makes possible quantum coherence in unusually long length scales.

3. This model led soon to a TGD inspired model for valence bonds [L2] (see `http://tinyurl.com/ycg94xpl`). The value of n for valence bond depends on the valence of the atom having larger electronegativity (more towards right along the row of the Periodic Table) and increases as one moves along the row: this guarantees that the bond energies vary only weakly along the row of the periodic table. The simple expectation form ordinary quantum theory is that the dependence of bond energy should be rather strong.

   The outcome is a vision about biochemistry and the roles of various valence bonds in metabolism. The valence bonds associated with atoms with high electronegativity carry especially larger metabolic energy identified as the difference of the bond energies for the actual value n_{bond} of n and its value n_{atom} for free atom. Catabolism would liberate this energy by reducing the values of n_{bond}.

2.2 Many-sheeted description of conductors

The first question is what electrons and elementary particles are at space-time level in TGD Universe.

1. In many-sheeted space-time elementary particles are two-sheeted structures consisting of two wormhole contacts, whose throats are connected by flux tubes at both sheets. The flux tubes at other sheet defining the magnetic body of the particle could have large value of $h_{eff}/h = n$ and be rather long. For instance, in atomic nucleus the flux tubes connecting nuclei to a nuclear string would be short with length L of order nucleon size but the flux tubes at the sheet defining magnetic body would be considerably longer - naturally given by nuclear length scale [K5, K9]. The length would be even longer for dark nuclei [L1].

2. Many-sheeted space-time predicts a hierarchy of space-time sheets and magnetic fields in various scales would correspond to these sheets and be represented as flux tubes. Flux tubes within flux tubes is what comes naturally in mind. Valence bonds would correspond to flux tubes defining only one level in this length scale hierarchy. Certainly this level is higher than elementary particle level, which corresponds to the Compton size of elementary particle.

3. Valence flux tubes could correspond to the magnetic body of the particle and have large valued of n. In accordance with the TGD view about valence bonds [L2] (see `http://tinyurl.com/ycg94xpl`) the value of n for valence bonds making possible also conductivity is larger than for free atoms.

   Remark: TGD Universe is fractal and this picture about elementary particles and their magnetic body is very similar to the view about galaxies as knots in long flux tube and having protuberances analogous to the flux loops and containing stars as sub-knots [L5] (see `http://tinyurl.com/ybbs9zhp`).

What makes the system a conductor?

1. Suppose that valence bonds indeed correspond to flexible loop like structures, which can be rather long for large values of n. Could the hopping of electrons between neighboring molecules (or atoms) be basically a topological process?

   Could the valence flux loops of neighboring molecules (say NiO) temporarily reconnect to form a pair of flux tubes connecting the molecules so that electrons can propagate along the these flux tubes between molecules?

   There would be no resistance during the flow along flux tube but the stopping at the end of the flux tubes would contribute to the resistance. In absence of electric field the currents are in random direction but the presence of electric field would make possible a net current.

2. One can try to relate this picture also to the standard description of conductivity obtained replacing many-sheeted space-time with that of special relativity so that all information about space-time topology is lost. What remains are the parameters U and t defined as matrix element of ΔU and the gap energy for the conduction band defined as $U - 2zt$.

   A de-localization of electrons occurs in conductivity due to temporary reconnections inducing hopping of electrons between neighboring sites. The increase of n increases various quantum scales. In particular, the length of valence bond increases and the wave functions for valence electrons are de-localized in a larger volume.

   Therefore the matrix elements of ΔU receive contributions from a volume, where ΔU is large. For flux tubes connecting neighboring unit cells it could be even larger than this.

   Also the value of U as expectation value of Coulombic energy for single site is affected. When the value of the competing parameter U becomes large enough, band gap becomes so large that conductivity is lost and one has Mott insulator.

3 Mott insulators in TGD framework

In TGD framework the new view about valence bonds and anti-ferromagnetism provides new insights about Mott insulators.

1. The valence bonds for oxides such as NiO should have high values of n and for certain critical parameter values (quantum criticality) n might become even higher than for ordinary valence bonds. This would increase the quantum coherence length measured by the flux tubes connecting neighboring molecules: the naivest guess is that it is proportional to n (for the atomic orbitals it is proportional to n^2). This makes makes possible quantum coherence in longer scales than usually possibly leading to a formation of Cooper pairs implying superconductivity at least in short scales at low enough temperatures.

2. Transition metal property is essential for being a Mott insulator. The table of Wikipedia article gives an overall view about transition metals (see `http://tinyurl.com/ydyqunm4`). There are 4 groups corresponding to the values $r = 4, 5, 6, 7$ labelling the rows of the Periodic Table.

   Ni atoms appearing in Mott insulator NiO and Cu atoms appearing in copper oxide high T_c superconductors belong to the group 4 of transition metals, which means that they belong to the fourth row of the Periodic Table (principal quantum number of highest valence electrons equals to 4). Ni and Cu are at the right end of the portion of 4th row containing transition metals. The value of n for copper oxides is predicted by TGD based model of valence bond to be highest in group 4 and second highest for Ni [L2] (see `http://tinyurl.com/ycg94xpl`). Copper oxides are therefore ideal candidates for high T_c superconductors in TGD Universe!

   For the groups 5, 6, and 7 the oxides of the elements towards the ends of these rows, in particular those of the rightmost elements in the group are Ag, Au, and Hs are good candidates for high T_c superconductors if the TGD based interpretation makes sense. One can also ask whether T_c could be higher for the transition metals of higher groups.

   Remark: ORMEs are precious metals belonging to 5th and 6th groups of transition metals and claimed to be superconducting at room temperatures. Their claimed healthy effects could be due to the large metabolic energy content of the valence bonds involved liberated when utilized.

3. Anti-ferromagnetism is also essential for Mott insulator property besides the property called "mottism" summarized above. Also copper oxides are anti-ferromagnetic (AFM) and the TGD based model relies on the existence of parallel flux tubes carrying magnetic fluxes with same magnitudes but opposite directions [K7, K8]. The members of Cooper pairs are at different flux tubes and form spin singlets.

4. An intriguing property of Mott insulators is the existence of bosonic excitations with charge 2e. They must consist of 2 electrons (see `http://tinyurl.com/ydyqunm4`) and are therefore natural candidates for the precursors of Cooper pairs in unconventional superconductivity.

3.1 Transition to non-conventional superconductivity

What could happen in the transition to non-conventional superconductivity?

1. Anti-ferromagnetism is a necessary ingredient. It requires the presence of flattened square shaped flux tube loops with opposite directions of magnetic flux for the opposite sides of the flattened square. Also the flux tubes defining the valence bonds and assignable to the magnetic bodies of electrons are present. The temporary reconnection of the valence flux loops would give rise to ohmic conductivity.

   Could the valence flux tubes temporarily reconnect with AFM flux tubes inducing the transfer of electrons to them so that supra current would flow along the resulting flux tube pairs and one would have high T_c superconductivity.

   There is however an objection against this idea. Valence electrons are responsible for ferromagnetism: can one really distinguish between the AFM flux loops and valence flux loops. Many-sheeted space-time suggests that this is spossible. AFM loops would correspond to a higher level in the hierarchy of space-time sheets than valence loops do. Cooper pairs reside at these flux tubes whereas Ohmic current carriers reside at the valence loops.

2. How exactly are the Cooper pairs formed? Are they formed as Cooper pairs with members assignable to neighboring lattice sites and are these pairs transferred to AFM flux tube pairs by temporary reconnections? If so, the basic mechanism giving rise to supra current would be purely topological.

   As already mentioned, Mott insulators are characterized by the existence of bosonic excitations with charge 2e, which must consist of 2 electrons (see `http://tinyurl.com/ydyqunm4`). This would suggest that they are precursors for the Cooper pairs of high T_c super-conductors appearing below the upper critical temperature T_{c1} but not yet giving rise to superconductivity in long length scales? The transition to superconductivity for Mott insulators would be analogous to the transition to super-conductivity for high T_c superconductors.

3. According to TGD based model of high T_c superconductors [K1, K2, K7, K8] the transition to superconductivity would take place at two steps. At higher critical temperature T_{c1} a phase transition to a state containing Cooper pairs takes place but there is no super-conductivity in long scales yet. Supra currents would be associated with AFM flux loops having the shape of a flattened rectangle such that magnetic fluxes have opposite directions at the opposites sides of the rectangle. At lower temperature T_c a phase transition to a genuine super-conductivity takes place: sequences of the flux loops would reconnect to much longer flux loops making possible macroscopic supra currents.

4 TGD description for the super-conductivity of graphene

The above general model for high T_c super-conductivity and Mott insulators can be applied also to graphene bi-layer.

1. Graphene sheets are hexagonal lattices formed from aromatic rings of 6 C-atoms. Delocalization occurs for valence electrons inside 6-rings and a further delocalization occurs as the hexagonal lattice is formed and gives rise to conductivity. The current flow would be along routes associated with the flux tube network formed from the hexagons. As already explained, in the TGD based model for valence bonds the value of $h_{eff}/h = n$ is higher for valence bonds than for atoms.

2. For the generic twist angle θ the graphene sheets behave like independent conductors with a weak interaction. For critical twist angles the system behaves as a single coherent unit and becomes Mott insulator. The increase of h_{eff} increases the energy of the valence bond increasing band gap so that it becomes difficult to kick electrons to valence band by thermal energy. Conductivity is lost. The increase of quantum coherence length can however lead to a formation of Cooper pairs (as in Mott insulators quite generally) and an applied electric field can kick the electrons to a new conduction band allowing super-conductivity.

3. The critical twist angle can be understood in terms of a generation of lattice like structure with an increased size of the lattice cell. At the nodes of this super-lattice the carbon atoms of two sheets would be directly above each other. The formation of this super-lattice is known as Moire effect (see `http://tinyurl.com/qchunes`).

   Cooper pairs would have periodic wave functions in the superlattice. Wave length would be equal to the lattice constant of the superlattice in the simplest situation. $h_eff/h = n$ view about dark matter would suggest that the members of Cooper pair are dark ($n = n_s$) and that the ratio of the lattice cells sizes for super-lattice (l_s) and the original lattice (l) equals to the ratio of corresponding values of n: $l_s/l_1 = n_s/n$.

4. Precursors of the Cooper pairs should be associated with the combination of flux tube networks defined by the two graphene lattices and would be transferred to AFM flux loops having longer length and reconnecting to long flux flux tube pairs.

   Since superconductivity occurs only for a critical twist angle, a pairing of flux tubes connecting the nodes of the super-lattice should take place. The members of Cooper pair should be associated with members of these flux tube pairs. The distance between Cooper pairs would have upper bound give by l_s.

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