About high T_c superconductivity and other exotic conductivities

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February 29, 2016

Abstract

During years I have been developing a model for high T_c superconductivity. The recent view relies on quantum criticality in more general sense than usually made possible by what I call zero energy ontology. Also the notions of magnetic flux tube and hierarchy of dark matters labelled by the values of Planck constant $h_{eff}/h = n$ are central. Besides super-conductivity there are various types of other exotic conductivities: one can say that condensed matter physics has experienced an inflation of poorly understood conductivities. In this article I propose a unified view about these phases and transitions between them relying on TGD based model of high T_c superconductivity.

1 Introduction

During years I have been developing a model for high T_c superconductivity (see https://en.wikipedia.org/wiki/High-temperature_superconductivity). The recent view is already rather detailed but the fact that I am not a condensed matter physicist implies that professional might regard the model as rather lopsided. Quite recently I read several popular articles related to superconductivity and various types of other exotic conductivities: one can say that condensed matter physics has experienced an inflation of poorly understood conductivities. This of course is an fascinating challenge for TGD. In fact, super string theorist Subir Sachdev has taken the same challenge (see http://tinyurl.com/hu4a27f).

In particular, the article about superconductivity (see http://tinyurl.com/h59yqn4) provides a rather general sketch about the phase diagram for a typical high T_c super conductor and discusses experimental support for the idea quantum criticality in standard sense and thus defined only at zero temperature could be crucial for the understanding of high T_c super conductivity.

The cuprates doped with holes by adding atoms binding some fraction of conduction electrons are very rich structured. The transition from antiferromagnetic insulator to ordinary metal involves several steps described by a 2-D phase diagram in the plane defined by temperature and doping fraction. Besides high T_c super conducting region the phases include pseudogap region, a region allowing charge oscillations, strange metal region, and metal region.

In the following I consider the general vision based on magnetic flux tubes carrying the dark $h_{eff}/h = n$ variants of electrons as Cooper pairs or as free electrons allowing to understand not only high T_c super-conductivity and various accompanying phases but also exotic variants of conductivity associated with strange and bad metals, charge density waves and spin density waves. One could also understand the anomalous conductivity of SmB_6 [L1], and the fact that electron currents in graphene behave more like viscous liquid current than ohmic current (see http://tinyurl.com/jlgd2we).

The TGD inspired model for the anomalous conductivity of SmB_6 as flux tube conductivity developed during last year [L1] forms an essential element of the mode. This model implies that Fermi energy controlled by the doping fraction would serve as a control variable whose value determines whether electrons can be transferred to magnetic flux tubes to form cyclotron orbits at the surface of the tube. Also the metals (such as graphene) for which current behaves more like a viscous flow rather than Ohmic current can be understood in this framework: the liquid flow character comes from magnetic field which is mathematically like incompressible liquid flow.

2 Background

In this section the phase diagram of high T_c superconductor, the crucial observation related to quantum criticality, and some models for high T_c superconductivity are briefly discussed.

2.1 The phase diagram and observation

The popular article "The Quantum Secret to Superconductivity" (see `http://tinyurl.com/h59yqn4`) tells about an article published in Nature [D1] (see `http://tinyurl.com/go9k8cs`) about the work of a group o researchers at the National Laboratory for Intense Magnetic Fields (LNCMI) in Toulouse, France led by Cyril Proust and Louis Taillefer.

The popular article contains a phase diagram, which gives a bird's eye of view about high T_c superconductors and provided the stimulus for this article. The diagram describes the phases of a doped cuprate (now yttrium barium copper oxide superconductor $YBa_2Cu_3O_7$, see `https://en.wikipedia.org/wiki/Cuprate`). Doping means an addition of impurities, which bind electrons and lead to the formation of holes. Also electron doping is possible. The diagrams contains several regions representing phases of the system.

The diagram (see **Fig. 1**), which probably should not be taken too literally, can be seen as a qualitative representation of the phase transition sequence leading from an antiferromagnetic insulator to a conducting metal. It is considerably more complex than the corresponding diagram for the ordinary insulator metal transition. One starts from un-doped antiferromagnetic insulator and increases the doping fraction and ends up with metal. The holistic strategy is to try to understand all transitions and phases appearing in the entire diagram using same basic model rather than the mere transition to super-conductivity.

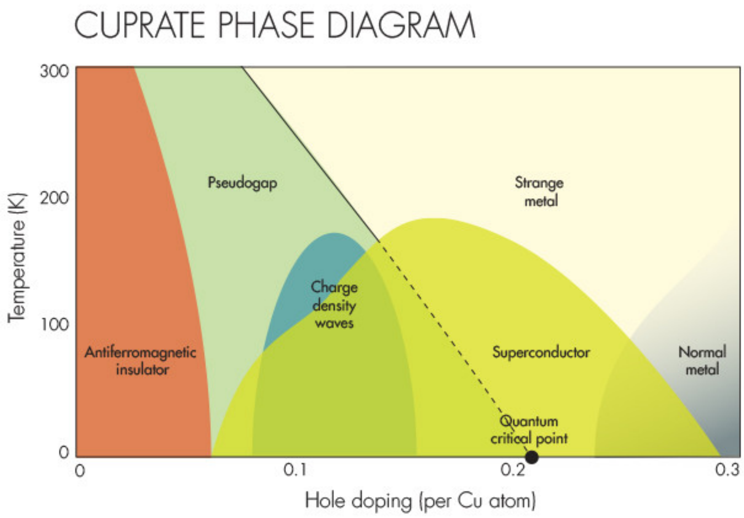

Figure 1: The phase diagram of typical high T_c superconductor

1. Above temperature dependent critical doping around $d = .05$ (meaning addition of impurities) a transition to so called pseudogap phase occurs. At a higher temperature dependent critical doping ratio varying in the range $(.05, .14)$ emerges a hill representing high T_c superconductivity.

2. There is also a parabola shaped region bounded at the top of super-conducting hill in which charge density wave define the ground state. In his phase kind of jerkwise conductivity but not yet superconductivity occurs. The piece of parabola is contained in doping fraction interval between $(.08, .13)$ (reader might disagree, I apologize for my bad eye sight).

3. At temperature above 170 K and for temperature depending doping ratio decreasing with temperature linearly pseudogap is transformed to a strange metal bounded by superconductor hill below. Farthest to the right is the ordinary metal phase bounded by superconducting hill and strange metal region. Critical doping fraction for the transition from superconductivity to ordinary conductivity decreases with temperature and is in the range $(.26, .29)$.

The challenge is to understand what these regions correspond physically and what happens in the transitions between them. The crucial observation is following. The researchers realized that the line representing the boundary between pseudogap and strange metal seems to continue below the super-conducting regions. Could one destroy the superdonducting region to see whether it meets the $T = 0$ axis at the bottom and could at this point quantum phase transition occur at critical value of doping?

This was done by putting the system to a strong magnetic field of 90 Tesla destroying the superconducting phase by making Cooper pair unstable. It was indeed observed that the number of holes per Cu atom - called charge carrier density (perhaps misleadingly) - increased by a factor 6 at this critical point - actually in its vicinity since $T = 0$ is not reachable exactly. The researchers think that this might be crucial guideline in attempts to understand high T_c superconductivity and I share their belief. The understanding of what really happens in the transition to superconductivity or rather in the transition from the pseudogap state to super-conductivity is the problem.

2.2 Alternative proposals for the mechanism of superconductivity

What has been observed is quantum critical point at $T = 0$ at which the density of holes per atom increases by a factor of 6. This does not mean that the superconducting charge carriers are Cooper pairs of holes. The phenomenon might have nothing to do with superconductivity in superconducting phase. The phenomenon is observed by using strong magnetic fields preventing superconductivity so that one in principles does not study the same system anymore.

Several hypothesis for the mechanism of super conductivity have been proposed and some of them are mentioned in the popular article (see `http://tinyurl.com/h59yqn4`) .

1. Spin density waves (mentioned in Wikipedia article but not discussed in the popular article) would take the role of phonons and induce the formation of Cooper pairs by a kind of water bed effect. These waves do not appear in the phase diagram. Now the Coulomb repulsion forces the members of Cooper pair to reside at different lattice sites and the outcome would be d-wave Cooper pair having a note at origin. In TGD the members of Cooper pair at parallel flux tubes so that also now d-wave is obtained for spin singlet state and p-wave for spin triplet.

2. Charge density wave fluctuations would somehow be involved with the formation of Cooper pairs. Phase diagram for charge density fluctuations does not support this picture since the superconducting regions is much larger. Transitions to superconductivity can happen from 4 regions: pseudo gap region, the regions with fluctuating charge density, strange conductor, and ordinary conductor. Also spin density wave fluctuations could have similar role.

3. A phase transition occurring to the anti-ferromagnetic phase is suggested to somehow induce the formation of Cooper pairs. The called Merlin-Wagner theorem stating the absence of breakdown of continuous symmetry in two-dimensional models of statistical physics at non-zero temperatures does not support this hypothesis. One could circumvent this problem by assuming that only patches forming kind of checkerboard consisting of super-conducting and non-superconducting regions can develop in 2-D. No checkerboards have been observed. Note that there is however an objection against Merlin-Wagner theorem. Antiferromagnetic order has been detected in undoped cuprates with the same 2-D structure.

Subir Sachdev is a super string theoretician, who has been developing superstring inspired methods - in particular AdS/CFT correspondence - to study quantum critical phenomena. Sachev and collaborators have developed methods for studying "strange metals". These systems are exceptional in that they do not have any quasiparticle excitations. Sachev has correctly predicted charge density fluctuations in high T_c superconductors and also proposed that the precursor for high T_c superconductivity would be what he calls fractionized Fermi liquid meaning fractional spin and charge. One would have something like ordinary conductivity but with fractional charges. This phase could correspond to strange metal.

3 TGD proposal for the mechanism of high T_c superconductivity

The challenge for TGD inspired qualitative model is to understand these phases in terms of magnetic flux tubes and dark electrons possibly forming Cooper pairs at them.

3.1 Formulation of the model

The starting point is the model developed hitherto.

1. Consider first Merlin-Wagner theorem as an objection against breaking of 2-D continuous symmetries. TGD suggests however a mechanism allowing a breakdown of 2-D continuous symmetries (by strong form of holography TGD space-time is almost 2-D as far as scattering amplitudes are considered: string world sheets and partonic 2-surfaces). The continuous symmetries in question include supersymplectic transformations having conformal structure meaning that the generators are labelled by conformal weights which come as integer multiples of generating weights. This symmetry breaking would lead from the original symmetry algebra to its sub-algebra isomorphic with the original. Just a zoom up of the original symmetry would be the outcome! Maybe Merlin and Wagner could tolerate this!

   Now one would have something different from a checkerboard of patches. There would be quantum critical phase in which a phase containing Cooper pairs at short flux tubes with Planck constant $h_{eff}/h = n_1$ and phase containing long flux tubes with $n_2 > n_1$ but no Cooper pairs at them. There would be fluctuationS between these phases. Fluctuation would have in ZEO as correlate space-time surface connecting three surfaces at opposite boundaries of CD such that the values of n would be different at them [L3] (see `http://tgdtheory.fi/public_html/articles/phasetransitions.pdf`).

2. The earlier model [L2] (see `http://tgdtheory.fi/public_html/articles/newsupercond.pdf`) identifies the pseudogap as quantum fluctuating phase in which there isA competition between short and long flux tubes pairs related by re-connections for short flux tubes containing Cooper pairs such that their members are at parallel flux tubes of pair carrying magnetic fields in opposite direction. Long flux tubes canot carry Cooper pairs and this together with fluctuations spoils macroscopic super-conductivity in pseudogap phase and makes it a poor conductor.

   Pseudogap is present in the density of states since part of electrons goes to the short flux tubes. The transition to superconducting phase identified in terms long flux tubes carrying Cooper pairs would occur when Cooper pairs go also to the long flux tubes and would be analogous to the percolation phase transition in which water begins to dribble through a sand layer. Pseudogap phase is quantum critical: zero energy ontology (ZEO), which allows to see quantum theory as a square root of thermodynamics at single particle level indeed allows quantum criticality also at non-vanishing temperatures.

3. Strange metal phase can be identified as a phase in which only short super-conducting flux tubes are present and carry supra currents but in short scales only. Since Cooper pairs have spin zero, the charged currents do not carry spin: this conforms with the observation that the resistance for spin currents has different temperature dependence than for charged currents. Therefore the generalization to 2-D case of the charge-spin separation possible in 1-D case

(but also in this case non gauge-invariant notion, (see `http://tinyurl.com/znsver8`) is not needed. Quite generally, the possibility of short scale $S = 0$ super conductivity could explain the charge-spin separation.

The fact that scattering leads from dark phase at flux tubes to ordinary phase could explain the linear temperature dependence of the resistance of strange metals. In ordinary metals the dependence is quadratic: the reason is that the number of initial and final state electrons is proportional to T. If the number of dark Cooper pair at flux tubes does not depend on temperature one obtains linear dependence.

The absence of quasiparticle excitations in strange metal would be due to the fact that Cooper pairs are dark and at magnetic flux tubes. Both n_1 and $n_2 > n_1$ phase would be present below critical doping fraction in the experiment discussed and would correspond to a situation in which there is fluctuation between the short length scale superconductivity and long length scale flux tubes not containing Cooper pairs. The strong magnetic field used in the experiment would not destroy the long flus tubes and the quantum critical phase would survive.

4. The quantum critical phase transition discussed in the article at zero temperature and critical doping fraction increases the number of holes per copper atom by a factor 6. Also this can be understood qualitatively. The transfer of electrons to dark Cooper pairs generates holes. In pseudogap region the long flux tubes do not carry Cooper pairs. As the phase transition occurs, only short flux tubes remain and accept pairs maximal number so that the number of holes per copper atom increases. Also the properties of pseudogap can be understood. Pseudo gap means a low density of states at certain points of Fermi surface (the point defines a preferred direction of current) and is known to be only in direction parallel to CuO bonds: this can be understood if flux tubes are parallel to them.

3.2 Charge density waves and spin density waves and their fluctuations

Can TGD say something interesting about charge density waves (see `https://en.wikipedia.org/wiki/Charge_density_wave`) and spin density waves (see `https://en.wikipedia.org/wiki/Spin_density_wave`)?

1. Charge density wave defines a ground state of the system having lower energy than the state with constant density of electrons. These waves are periodic standing waves with wavelength $\lambda = \hbar/k_F$. Wavelength does not in general correspond to a multiple of lattice constant. In presence of these waves conduction occurs in random jerkwise fashion like the water dribbling from faucet. The standard explanation for the jerkwise current is that the charge density wave is in a potential well caused by defect and when the electric field exceeds the critical value it is released and slides generating an ohmic current. Below the threshold the system would behave as an insulator.

2. Spin density waves are very similar to charge density waves: instead of charge, the direction of spin varies in oscillatory manner with wavelength defined by Fermi wave vector in ground state. Also now a current is formed in direction of the magnetic field above critical value of magnetic field. Sliding mechanism is proposed also now as the underlying mechanism of conductivity.

3. The key question is where a spatially varying fraction of charge/spin goes as charge/spin density wave is formed. In TGD Universe the answer would be rather obvious: "To flux tubes!". Both charge density wave and spin density could involve a sequence of magnetic flux loops with a period defined by k_F so that supra currents could flow below this length scale. Charge density wave could result from a transfer of electrons to flux tubes producing oscillator charge density at the flux tube inducing corresponding charge density oscillation in lattice. In the case of spin density wave the spin directions would be correlated at flux tubes and induce corresponding correlation in the lattice.

4. The conductivity associated with charge density wave above critical electric field could correspond to a kind of premature and temporary phase transition to super-conducting phase in

which long flux tubes contain Cooper pairs but are still unstable. In the transition to superconductivity a reconnecting to long flux loop looking like long and thin rectangle would be formed by reconnections. One would have a system fluctuating between short and long scale superconductivities. One could of course consider also sliding of the flux tubes but this does not seem so plausible option in TGD framework.

The conductivity induced by critical magnetic field could be understood if the magnetic field induced a phase transition reconnections transforming the periodic short flux tube structure to a pair of long flux tubes. Why the magnetic field would induce this, is not clear. Same question of course applies in the case of the critical electric field inducing the generation of current in charge density wave.

3.3 The role of doping fraction

Can one understand the role of doping fraction?

1. The number of holes per copper atom depends on the doping fraction. The holes would be created when dark Cooper pairs are generated. If the density of dark Cooper pairs increases dramatically at critical doping fraction, the density of holes must increase. Somehow the over-critical doping fraction would favor the formation and stability of short dark flux tubes. Maybe it becomes energetically more favorable for electrons to go to flux tubes. This might relate to cyclotron energy proportional to h_{eff} at flux tubes and Fermi energy E_F: a kind of resonant transfer suggests itself.

   For some time ago I constructed a model for the anomalous conductivity of SmB_6 in external field in terms of Haas-van-Alphen effect for non-standard value of h_{eff} [L1] (see `http://tgdtheory.fi/public_html/articles/SmB6.pdf`). A resonant transfer of electrons to flux tubes occurs if the energy energy at the surface of the Fermi sphere corresponds to energy for a cyclotron orbit at the surface of the flux tube. The largest orbit at Fermi sphere would be at the surface of the flux tube. This implies the occurrence of Haas van Alphen as a periodic dependence of magnetization on the value of external magnetic field $1/B$ and also explains also the anomalous conductivity of SmB_6 as flux tube conductivity occurring when the resonance condition is satisfied.

   A rather natural expectation is that same happens now. The doping fraction would control the value of Fermi energy, and this in turn would control the rate for the leakage of electrons to Cooper pairs at flux tubes by resonance condition. If the dependence of the Fermi energy on doping fraction is slow this could allow to understand why an entire range of doping fractions is possible. That the electrons must have Fermi energy must correlate with the wave length of of charge and spin density waves. The length of the short flux tube loop corresponds to Fermi wave vector.

   There is also a feedback effect involved. When electrons become Cooper pairs at short flux tubes, their density in lattice is reduced and this reduces Fermi energy so that resonance condition might fail to be satisfied. If flux tubes carry monopole flux, flux is quantized and the value of the magnetic field depends on the thickness of the flux tube, which could also be dynamical.

2. Below critical doping fraction long flux tubes would be possible but would be unstable and unable to carry stable Cooper pairs. The reason could be that the resonance condition for the transfer fails to be satisfied (the thickness of long flux tubes would not satisfy the resonance condition). Superconductivity and strange metal property would disappear above certain temperature dependent value of the doping fraction. Also this could be understood in terms the failure of the resonance condition for both short and long flux tubes. In the charge density wave region the resonance condition would be satisfied for the long flux tubes.

3.4 Connection with Sachdev's ideas

Sachdev's ideas mentioned above have correspondences in TGD. AdS/CFT is central in Sachev's approach and it has been also proposed as a solution of so called sign problem (see `http://`

tinyurl.com/h9ogjjd) plaguing QFT models and statistical physics models in dimension $D \geq 3$. Sign problem gives one additional good reason for the localization of the induced spinor fields at 2-D string world sheets in TGD framewwork [K1].

1. AdS/CFT relies on conformal symmetry: in TGD framework the conformal symmetry is generalized to super-symplectic symmetry and other symmetries having conformal structure and assignable to the boundary of light-cone and to the light-like orbits of partonic 2-surfaces at which the induced metric changes its signature from Minkowskian to Euclidian.

2. TGD Universe is quantum critical so that also this aspect is shared. AdS/CFT correspondence relies on holography: in TGD framework one has strong form of holography and one can say that the 10-D bulk is replaced with 4-D space-time surface in $M^4 \times CP_2$.

3. Charge and spin fractionization are plausible also in TGD: the unit would be scaled down by $1/n$ ($h_{eff}/h = n$) and in twistorial approach [K2] this is understood quite satisfactorily.

4. Also in TGD the precursor would be strange metal. I have already explained how charge spin separation reflecting itself as different temperature dependences of resistances for charged and spin currents and the linear dependence of resistivity on temperature can be understood.

There are also differences. In TGD framework strange conductor would be flux tube superconductor in short length scales with $h_{eff}/h = n_1 < n_2$ rather than fractional ordinary conductor.

3.5 Bad and strange metals and metals behaving like water

Besides high T_c superconductors there are also other exotic conductors such as strange and so called bad metals http://tinyurl.com/zzzyenp) difficult to understand using the ideas of existing condensed matter physics.

In the case of bad metals (see http://tinyurl.com/k54k9oa) the conductivity is low but is preserved to too high temperatures. The problem is that if the electrons scatter as usual the time τ between collisions becomes too small and at higher temperatures Uncertainty Principle requiring $T \times \tau \geq h$ fails to be satisfied. Quite recent proposal [D2] is that current carrying electrons somehow disappear and this fluctuation is not only responsible for low but on-vanishing conductivity. These fluctuations could be due to the quantum critical fluctuations transforming electrons to Cooper pairs at short flux tubes. Bad metal would be unable to decide whether to be an insulator or strange metal.

Also graphene behaves in a strange manner (see http://tinyurl.com/hffdl8s) in the sense that currents behave more like viscous liquid flow rather than ohmic currents. The presence of vortices is a basic signal about this. A model assuming a negative resistance allowing electrons to move in "wring direction" in electric field is considered as an explanation. To me this option looks tricky.

Liquid like behavior might be understood if the currents flow at magnetic flux tubes. Magnetic field is mathematically analogous to an incompressible liquid flow. Flux tubes would be like water pipes forming a network and the topology of the ohmic currents would reflect the topology of this loopy magnetic network. The direction of the electric field inside flux tube space-time sheet would be parallel to the flux tube so that negative resistance would not be required: electric field would change direction locally rather than resistance its sign. In long scales at the space-time sheets assignable to the ordinary matter the direction of electric field would be constant. The phenomenon would reflect many-sheetedness of space-time lost in the gauge theory limit of TGD. Note that if currents are supra currents along flux tube pairs in short scales, there would be no resistivity in these scales.

To sum up, the notions of magnetic flux tube and dark matter hierarchy suggest common mechanisms for all the exotic conductivities. From this it is of course a long way to quantitative models.

REFERENCES

Condensed Matter Physics

[D1] Badoux S et al. Change of carrier density at the pseudogap critical point of a cuprate superconductor. *Nature.* Available at:http://tinyurl.com/go9k8cs, 2016.

[D2] Jaramillo R et al. Origins of bad-metal conductivity and the insulator-metal transition in the rare-earth nickelates. *Nature Physics*, 10:304–307, 2014.

[D3] Sebastian SE et al. Unconventional fermi surface in an insulating state. *Science.* Available at: http://www.sciencemag.org/content/early/2015/07/01/science.aaa7974, 349(6243):605–607, 2015.

Books related to TGD

[K1] Pitkänen M. Why TGD and What TGD is? In *Topological Geometrodynamics: an Overview.* Onlinebook. Available at: http://tgdtheory.fi/public_html/tgdview/tgdview.html#WhyTGD, 2013.

[K2] Pitkänen M. From Principles to Diagrams . 2016.

Articles about TGD

[L1] Pitkänen M. Does the physics of SmB_6 make the fundamental dynamics of TGD directly visible? Available at: http://tgdtheory.fi/public_html/articles/SmB6.pdf, 2015.

[L2] Pitkänen M. Quantitative model of high T_c super-conductivity and bio-super-conductivity. Available at: http://tgdtheory.fi/public_html/articles/newsupercond.pdf, 2015.

[L3] Pitkänen M. Whats new in TGD inspired view about phase transitions? . Available at: http://tgdtheory.fi/public_html/articles/phasetransitions.pdf, 2016.