What happens in the transition to superconductivity?

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Abstract

This article was inspired by the findings related to a quantum phase transition between 2-D insulator and superconductor. The basic question of how two-dimensional superconductivity can be destroyed without raising the temperature. The ordinary phase transition to superconductivity is induced by thermal fluctuations. Now the temperature is very close to the absolute zero and the phase transition is quantum phase transition induced by quantum fluctuations. One of the unexpected findings was that magnetic vortices representing fluctuations abruptly disappear just below the critical electron density for the transition.

This gives important hints concerning the question how the transition to superconductivity could take place in the TGD Universe, where two kinds of magnetic flux tubes are predicted. Monopole flux tubes with a closed 2-surfaces as cross section are proposed to be carriers of Cooper pairs. The disk-like, Maxwellian, flux tubes for which electron current creating the magnetic field would emerge when superconductivity fails. The proposal is that a pair of disk-like flux tubes fuse to a mopole flux in the transition to superconductivity. One can also understand the abrupt disappearance of the fluctuations.

The model extends to a model of high Tc superconductivity providing a quantitative understanding of the energetics. of the superconductivity with an essential role played by the effective Planck constant.

Contents

1 Introduction

I learned about very interesting discoveries related to the quantum phase transition between the ordinary and superconducting phase [D1] (see this).

These kinds of findings are very valuable in the attempts to build a TGD based view of what exactly happens in the transition to super-conductivity. I have developed several models for high Tc superconductivity [K1, K2] but there is no single model. Certainly, the TGD based view of magnetic fields distinguishing them from their Maxwellian counterparts is bound to be central for the model. However, the view about what happens at the level of magnetic fields in the transition to superconductivity, has remained unclear.

Consider first the findings of the research group. The basic question of how two-dimensional superconductivity can be destroyed without raising the temperature. The ordinary phase transition to superconductivity is induced by thermal fluctuations. Now the temperature is very close to the absolute zero and the phase transition is quantum phase transition induced by quantum fluctuations.

1. The material under study was a bulk crystal of tungsten ditelluride (WTe2) classified as a layered semi-metal. The tungsten ditelluride was converted into a two-dimensional material consisting of a single atom-thin layer. This 2-D material behaves as a very strong insulator, which means its electrons have limited motion and hence cannot conduct electricity.

2. Surprisingly, the material exhibits a lot of novel quantum behaviors, in particular, a switching between insulating and superconducting phases. It was possible to control this switching behavior by building a device that functions like an "on and off" switch.

3. At the next step, the researchers cooled the tungsten ditelluride down to exceptionally low temperatures, roughly 50 milliKelvin (mK). Then the material was converted from an insulator into a superconductor by introducing some extra electrons to the material. It did not take much voltage to achieve the superconducting state. It turned out to be possible to precisely control the properties of superconductivity by adjusting the density of electrons in the material via the gate voltage.

4. At a critical electron density, the quantum vortices rapidly proliferated and destroyed the superconductivity. To detect the presence of these vortices, the researchers created a tiny temperature gradient on the sample, making one side of the tungsten ditelluride slightly warmer than the other. This generated a flow of vortices towards the cooler end. This flow generated a detectable voltage signal in a superconductor, which can be understood in terms of the integral form of Faraday's law. Voltage signals were in nano-volt scale.

Several surprising findings were made.

1. Vortices were highly stable and persisted to much higher temperatures and magnetic fields than expected. They survived at temperatures and fields well above the superconducting phase, in the resistive phase of the material.

2. The expectation was that the fluctuations perish below the critical electron density on the non-superconducting side, just as they do in ordinary thermal transition to superconductivity.

   In contrast to this, the vortex signal abruptly disappeared when the electron density was tuned just below the critical value of density at which the quantum phase transition of the superconducting state occurs. At this critical (quantum critical point (QCP) quantum fluctuations drive the phase transition.

These findings give important hints concerning the question how the transition to superconductivity could take place in the TGD Universe, where two kinds of magnetic flux tubes are predicted. Monopole flux tubes with a closed 2-surfaces as cross section are proposed to be carriers of Cooper pairs. The disk-like, Maxwellian, flux tubes for which electron current creating the magnetic field would emerge when superconductivity fails. The proposal is that a pair of disk-like flux tubes fuse to a mopole flux in the transition to superconductivity. One can also understand the abrupt disappearance of the fluctuations.

2 The interpretation of the findings in the TGD framework

What could be the interpretation of these findings in the TGD Universe and could they give hints for a more precise formulation of the TGD inspired model?

2.1 TGD view of high Tc superconductivity

Conside first the general TGD based view of high Tc superconductivity.

1. TGD leads to a rather detailed proposal for high Tc - and bio-superconductivity. There are reasons to think that this model might work also in the case of low temperature superconductivity, in particular in the proposed situation with one-atom-thick layer [K1, K2] [L1, L2].

2. The unique feature of the monopole flux tube is that its magnetic field needs no currents as a source. The cross section of the flux tube is not a disk, but a closed 2-surface. There is no boundary along which the current could flow and generate the magnetic field. In the absence of these ohmic boundary currents there is no dissipation and the natural interpretation is that electrons form Cooper pairs.

   These monopole flux tubes are central for TGD based physics in all length scales and explain numerous anomalies related to the Maxwellian view of magnetic fields. The stability of the Earth's magnetic field and the existence of magnetic fields in cosmic scales are two examples.

3. There are also ordinary flux tubes with disk-like cross sections for which current along the boundary creates the magnetic field just like in an inductance coil. The loss of superconductivity means generation of these disk-like magnetic vortices with quantized flux created by ordinary current at the boundaries of the disk-like flux quantum.

   The monopole flux has a cross sectional area twice that of disk-like flux tube so that one can see the monopole flux tube as being obtained by gluing two disk-like flux tubes along the boundaries. The signature of the monopole flux tube is that magnetic flux is twice that of ordinary flux tubes.

4. Whether the disk-like flux tubes are possible in the TGD Universe has remained uncertain. My latest view is that they are and I have written a detailed article about how boundary conditions could be satisfied at the boundaries [L3].

   The orbits of the disk-like boundaries would be light-like 3-surfaces. This is not in conflict with the fact that the boundaries look like static structure. The reason is that the metric of the space-time surface is induced from that of $M^4 \times CP_2$ and the large CP_2 contribution to the induced 3-metric makes it light-like. One might say that the boundary is analogous to blackhole horizon.

2.2 What could happen at the quantum critical point?

The above picture allows us to sketch what could happen at the quantum critical point.

1. Both monopole flux tubes and disk-like flux tubes are present at the critical point. Monopole flux tubes dominate above the critical electron density whereas disk-like flux tubes dominate above it. In the transition pairs of disk-like flux tubes fuse to form monopole flux tubes and electrons at the boundaries combine to Cooper pairs inside the monopole flux tube and form a supra current. The transition would be a topological phase transition at the level of the space-time topology and something totally new from the standard model perspective.

2. Cyclotron energy scale, determined by the monopole flux quantization and flux tube radius, is expected to characterize the situation. The difference of the cyclotron energies for the monopole flux tube with Cooper pair and for two disk-like flux tubes with one electron should correspond to the binding energy of the Cooper pair. If the thermal energy exceeds this energy, superconductivity is lost. The disk-like flux tubes can however remain stable.

3. The transition could involve the increase of the effective Planck constant h_{eff} but its value would remain rather small as compared to its value of high Tc superconductivity. The value of h_{eff} should be correlated with the transition temperature since the difference of total cyclotron energies would be proportional to h_{eff}.

This picture does not yet explain why the vortices suddenly disappear at the critical electron density. The intuitive guess is that the density of electrons is not high enough to generate the disk-like monopole flux tubes.

1. Suppose that these flux tubes have a constant radius and fill the 2-D system so that a lattice like system consistent with the underlying lattice structure is formed.

2. There must be at least 1 electron per flux tube to create the magnetic field inside it. The magnetic flux is quantized and if the boundary of the disk contains single electron, the number of electrons per flux tube area S is 1: the density of electrons is $n = 1/S$. If the electron density is smaller than this, the formation of disk-like flux tubes is not possible as also the transition to superconductivity.

2.3 How does the model relate to the earlier model of high Tc superconductivity?

This proposal is *not* consistent with the earlier TGD based model for high Tc superconductivity [K1, K2]. In high Tc superconductivity there are two critical temperatures. At the higher critical temperature T_{c1} something serving as a prerequisite for super-conductivity appears. Superconductivity however appears only at a lower critical temperature T_c.

The earlier TGD based proposal is that the superconductivity appears at $T_{c1} \geq T_c$ in a short length scale so that no long scale supra currents are possible. The magnetic flux tubes would form short loops. At T_c the flux loops would reconnect to form long flux loops. The problem with this option is that it is difficult to understand the energetics.

The option suggested by the recent findings, is that disk-like half-monopole flux tubes carrying Ohmic currents at their boundaries are stabilized at T_{c1}. At T_c they would combine to form monopole flux tubes.

1. The difference ΔE_c of the cyclotron energies of the monopole- and non-monopole states would naturally correspond to T_c whereas the cyclotron energy scale $E_c = \hbar_{eff} eB/m$ of the non-monopole state would correspond to T_{c1}.

2. In the first approximation, the value of B is the same for the two states. For the non-monopole state the electrons reside at the boundary and the effective harmonic potential energy is maximal. Quantum mechanically $l_z = 1$ state would be in question. Spins give rise to a Larmor contribution to energy and for total spin =0 these contributions would sum up to zero.

   Thermal fluctuations cannot provide energy for the formation of the half-monopole states. An incoming electron which does not rotate along the flux tube has longitudinal energy and part of this energy can be transformed to magnetic energy as the half-monopole flux tube is formed. Electrons would slow down somewhat.

   For the monopole state Cooper pair resides in the interior so that the cyclotron energy is smaller in this case. $l_z = 0$ state is natural in this case. Spins are opposite. This gives $\Delta E_c < 0$. The simplest interpretation is that the binding energy of the Cooper pair corresponds to this contribution but there could be an additional contribution.

3. If the value of h_{eff} is the same for the pair of half-monopole flux tubes and monopole tube states, both E_c and ΔE_c scale like h_{eff}/h. Also the critical temperatures T_c and T_{c1} would scale like h_{eff}/h. High Tc superconductivity would therefore provide a direct support for the hierarchy of Planck constants.

2.4 What one can one say about the incoming state?

What can one say about the incoming state, which must transform to the two half-monopole flux tubes? Suppose that it consists of some kinds of flux tubes.

1. There would be no longitudinal magnetic field if the electrons move along straight lines instead of rotating around the flux tube.

2. TGD predicts two kinds of flux tubes [L4] with a closed cross section: monopole flux tubes and Lagrangian flux tubes. For monopole flux tubes the induced Kähler form has a quantized flux over the closed cross section of the flux tube.

For Lagrangian flux tubes, which are of the form $X^2 \times Y^2 \subset M^4 \times CP_2$, the induced Kähler form vanishes. X^2 can have a boundary. Both $X^2 \subset M^4$ and $Y^2 \subset CP_2$ are Lagrangian manifolds since the twistor lift of TGD implies that also M^4 has the analogs of Kähler structure and symplectic structure algebraically continued from that of E^4.

3. Incoming flux tubes could be Lagrangian flux tubes with electrons moving along straight-lines ($l_z = 0$). Note that by their 2-dimensionality, X^2 and Y^2 allow complex structure determined by the induced metric so that the holography= holomorphy principle holds also for these 4-surfaces.

2.5 An overall view of superconduction

What could happen in the superconduction would be as follows.

1. First a pair of Lagrangian flux tubes with $l_z = 0$ representing incoming current transforms to a pair of half-monopole flux tubes with $l_z = 1$ electrons and electrons slow down somewhat.
2. After this half-monopole flux tubes fuse to form a monopole flux tube carrying a Cooper pain in $l_z = 0$ state. In $E^3 \setminus B^3$ (3-space with a hole) this transition is visualizable as a gluing of two hemispheres to form a sphere around the hole.
3. The reverse of this process would take place at the second end of the current wire where the current flows out.

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